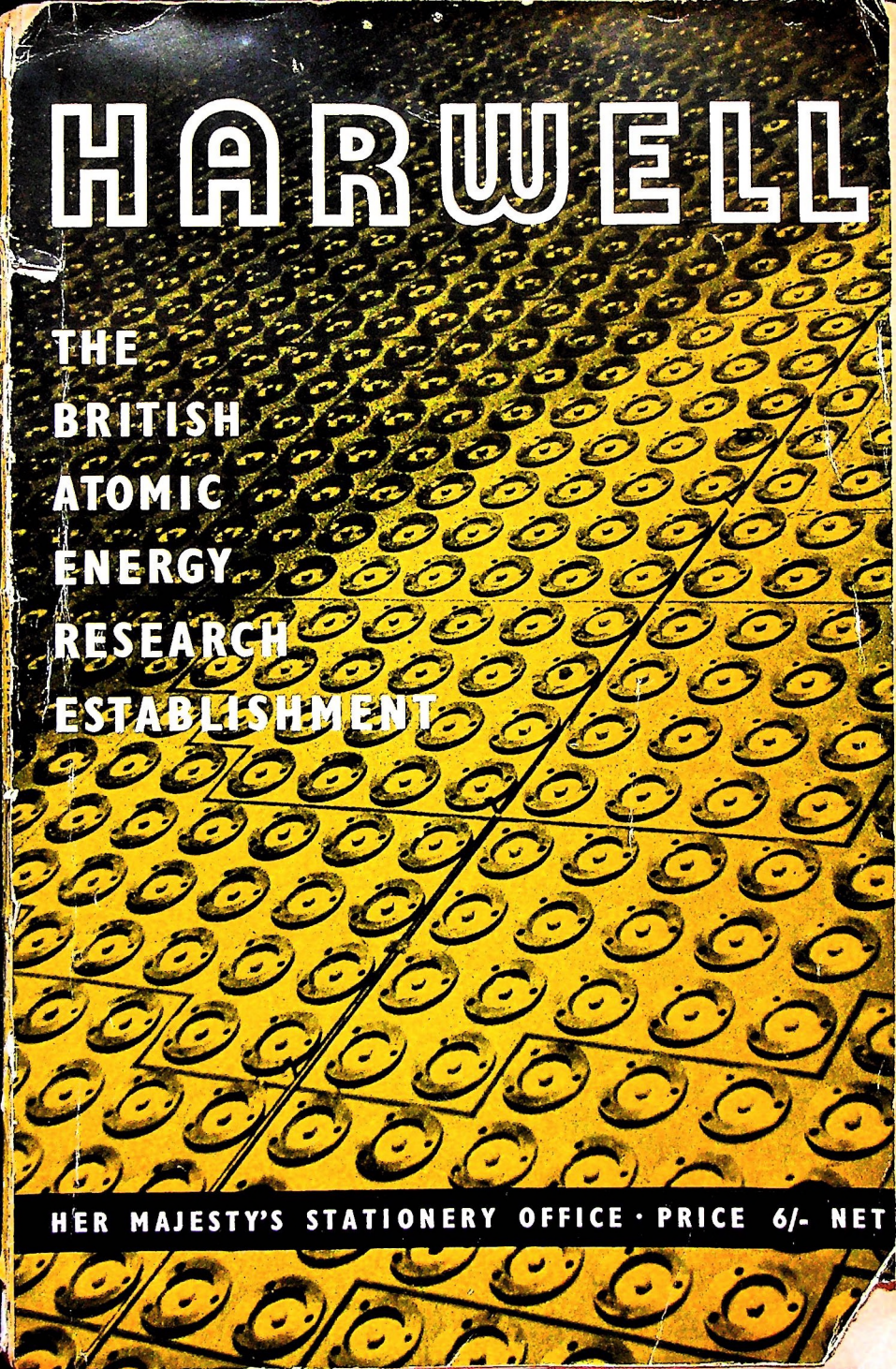
HARWELL

THE BRITISH ATOMIC ENERGY RESEARCH ESTABLISHMENT



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1946-1951

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PREFACE

THE purpose of this account is to present to the general reader a connected story of the work and problems of the Atomic Energy Research Establishment at Harwell from its inception in 1946 to the end of 1951. It has been impossible in this booklet to describe all the work in progress, and in some cases, particularly Chapter 8, there has had to be a rather arbitrary selection. The reader will find that some of the work mentioned has already been published in the daily press or in scientific journals, but it has been included again either to make an account complete, or to show the relation of the work to the programme as a whole.

PREFACE TO FIFTH IMPRESSION, 1956

This reprint of "Harwell" has been produced, without any alterations in the text, to meet the continual demand there has been for the book since it went out of print. Two major changes have taken place since the book was written. First, most of the work for the production programme, described in Chapter 3, has been completed. Second, the programme of work on nuclear power, described in Chapter 5, is now superseded by that described in the White Paper on this subject (Cmd. 9389) issued in February, 1955.

More recent work carried out by the Atomic Energy Research Establishment is described in a sequel to the present volume, Atomic Energy Research at Harwell (London, Butterworth, 1955) and in the first Annual Report of the United Kingdom Atomic Energy Authority (London, H.M.S.O., 1955).

ONE

THE ATOMIC ENERGY RESEARCH ESTABLISHMENT: ITS ORIGIN AND ORGANIZATION

THE Atomic Energy Research Establishment at Harwell was founded in 1946. That however is merely the year of its birth; its gestation was long going far back into the war-time research into the application of the process of nuclear fission which culminated in the atomic bomb. The story of that enterprise has been told elsewhere and this is not the place to repeat it. There are however certain details that must be brought into sharper focus if the origins of the Establishment and its character are to be understood. For scientific establishments are as individual as men and have characters as distinctive. And their characters spring often from the circumstances of their origin. That is true of Harwell at least, and because the character of Harwell is in many ways unique it is desirable to glance at its origins.

It will be recalled that the years 1938 and 1939 saw the announcement of the basic facts about the fission of the uranium nucleus. These discoveries, which were made in universities in Europe, were at once confirmed and extended by nuclear physicists in the United Kingdom and the United States. To these men the apparently recondite observations had tremendous practical implications, for they indicated that a self-sustaining fission reaction could probably be produced in which enormous quantities of energy would be released; moreover it was likely that the reaction could be made to go very quickly and the energy released with explosive violence, or that it could be slowed down and brought under control, a fire rather than an explosion. But this country was then at war; the possibility of a new explosive of unprecedented power inevitably attracted first attention. The possibility was speedily and independently brought to the notice of their respective Governments by leading scientists in this country and in America. From these beginnings sprang the enormous research effort and production enterprise, ultimately concentrated in the United States, which resulted in the atomic bomb. In this enterprise the physicists and chemists from the universities were working on production problems by the side of engineers from the largest industrial organizations. Many of the problems called for university scientists who were in the forefront of fundamental research. In this country it was from Liverpool and Birmingham, from Oxford and Cambridge, and from other universities that the results first began to flow, and it was from universities that most of the men were drawn to join the war-time projects in the United States and Canada.

This essential thread, the intimate participation of university research scientists in a national atomic energy project, was not broken by the end of the war. When the Prime Minister announced, in the House of Commons on 29th October, 1945, that the Government had decided " to set up a research and experi-

mental establishment covering all aspects of the use of atomic energy", it was axiomatic that the nucleus of its staff would be formed from such of these men as were willing to postpone, or to abandon, their return to academic life.

Mr. Attlee announced at the same time that responsibility for atomic energy was being transferred from the Department of Scientific and Industrial Research to the Ministry of Supply. Dr. J. D. (later Sir John) Cockcroft was appointed Director in January, 1946, and building began in April, 1946. The site chosen was the permanent R.A.F. aerodrome at Harwell, Berkshire. This choice was made on the grounds that an R.A.F. station provided a nucleus of accommodation, including large hangars suitable for pile buildings, and a prepared site with roads. In addition, Harwell was not too far from London and only 12 miles from Oxford, so enabling close University contacts to be maintained.

By the end of 1946 the first stage of development had passed into history; there was now a growing need for engineers of all kinds, metallurgists, chemists with industrial experience, a great variety of experts in almost every branch of pure and applied science. The rapidly growing Harwell staff came in from all quarters; its members were drawn from the British teams recently returned from the United States and Canada, from groups that had continued working in this country, from industry and from other Government establishments as well as from the universities.

At the present time much of the work is by its nature intimately connected with fundamental research going on in universities, and, so far as it is not secret, is discussed at scientific conferences and reported in scientific journals, while another large part, which tends to include more technology and practical experience and is therefore often secret, depends on close collaboration with industry in many different fields.

In addition there are many phases of the programme which call for day-to-day contact with other research and administrative departments of Government, and above all, with the atomic energy production organization in the Ministry of Supply. The formation of this organization was announced by the Prime Minister on 29th January, 1946, when he said that its purpose would be to produce fissile material in sufficient quantity " to enable us to take advantage rapidly of technical developments as they occur, and to develop our programme for the use of atomic energy as circumstances may require". The Headquarters of the production organization is at Risley, in Lancashire.

Harwell then is the research branch, and the Risley organization the production branch, of the British atomic energy effort. Harwell's tasks are to do fundamental research and development in all aspects of atomic energy, and to give every assistance to the production branch both by providing scientific and technical data, and by arranging contracts with industry for the pilot scale production of essential materials such as uranium and graphite. In the next chapter we shall review the programmes of research that have been laid down to achieve these ends.

The organization of the scientific part of the Establishment is simple. Under the Director there are twelve Divisions, the larger of which are the size of a large university research school, under a Division Head having a status comparable

with that of a university professor. They include Chemistry, Chemical Engineering, Engineering, Metallurgy and Physics Divisions. A complete list, with Division Heads, is given in Appendix A to this account. In addition the Medical Research Council has established a Radiobiological Research Unit at Harwell under the direction of Dr. J. F. Loutit.

An Establishment of this size needs supporting services on a corresponding scale. There are a large drawing-office and engineering workshops to design and make the apparatus needed by scientists. Administrative staff are required to deal with problems such as housing, recruitment, transport and stores. Maintenance, typing and cleaning have to be done and many other services provided without which the scientific work could not go on. But there is not space to describe them in this account and we will turn now to Harwell's research programmes and the progress that has been made in fulfilling them.

TWO

THE PROGRAMMES OF WORK AT HARWELL

WE have seen that Harwell has been given two main tasks. First it is to conduct research into all aspects of atomic energy; second it is to advise the production organization and furnish it with the scientific and technical information that it needs. These two commitments have led to the formulation of programmes of work for Harwell which will be the subject of the next six chapters of this account. In the present chapter a brief outline will be given of the aims and extent of each programme.

The primary piece of apparatus in all this work is the atomic pile or nuclear reactor. Reactors are needed for fundamental research; reactors produce fissile material; and reactors will be the means by which nuclear energy is converted into electrical or mechanical power. It follows then that the study and development of reactor technology is Harwell's primary interest and its first constructional task was to build one of these machines. Work to this end began at Chalk River, where the design of two graphite-moderated piles was undertaken. The first of these, the low-powered Gleep, was completed in August, 1947; the second, the higher-powered Bepo, in July, 1948. These two piles are essentially experimental tools, but the experience gained in their operation has been of great value in the design of the larger plutonium-producing piles. For this reason, and since the engineering design of Bepo was done by staff of the production organization at Risley, an account of their development will be given in the chapter dealing with the production programme.

By production programme is meant that part of the research programme which bears directly on the production of fissile material. In its later stages it consists of two parts, the first being concerned with the design of the Windscale production piles, the second with the design of a chemical separation plant. The Windscale piles, like Gleep and Bepo, are graphite-moderated, air-cooled units; however, they differ from Gleep and Bepo in many important respects, and their design posed many new problems. A considerable amount of research on their design has been done at Harwell, much of it utilizing Bepo as an experimental tool. The large-scale chemical separation of plutonium from uranium, on the other hand, had not been tackled in this country before. It set unique problems which are being tackled by the Establishment's chemists and chemical engineers aided by Risley and by industrial contractors. In addition to research on the broad principles of the processes, there is much work to be done on the materials to be used in the various equipments. This programme is discussed at length in Chapter 3.

There is one production programme which has been made the responsibility of the research side at Harwell: that is the production of radioisotopes. These are made in Bepo as a by-product of its use for other purposes. A part of the

production (that demanding very long irradiations in the pile) may be transferred later to the Windscale piles, but the bulk of it will continue to be done at Harwell. The isotopes are supplied to hospitals and other medical users, to universities and to industry. The work involves research on separating and standardizing the isotopes, and on their application to the solution of specific industrial problems. Harwell is also responsible for the supply of certain stable isotopes, separated by the electromagnetic method, by thermal diffusion, chemical exchange, and low-temperature distillation columns. The work on both radioactive and stable isotopes is discussed in Chapter 4.

The next programme to be considered is directly concerned with the application of nuclear fission to the generation of usable power. The fact that the fission of one pound of uranium 235 would release energy equivalent to burning 1,000 tons of coal is well known and the mechanism of the process is understood. The problem that has yet to be solved is how to release this energy in such a manner that it can be readily and economically converted into some such useful form as steam or electric power. The final solution of this problem is still some way off. The general principle proposed is that a nuclear reactor shall be used as a furnace to produce heat, which can then be transformed into mechanical energy. The questions are, what is the best kind of reactor for the purpose, and what is the most efficient way of getting the heat out of it and making it do mechanical work. If heat is to be converted into power efficiently it is necessary that the source of heat shall be at a high temperature. Reactors of the type so far built for plutonium production run at too low temperatures to be efficient furnaces for boilers or gas turbines. Moreover, they are not economical in their use of the nuclear fuel, uranium. Several designs have been considered for reactors suitable for operation at higher temperatures and for "breeding" new fissile material from non-fissile material, and one of these has reached the stage of detailed study by a large engineering firm. However, much has still to be learned about the combined effects of high temperatures and intense neutron, β- and γ-ray bombardments on constructional materials. Until these problems are solved and some experience gained in the operation of reactors no reliable estimates can be made of the economics of nuclear power production. The programme is therefore primarily one of reactor development and it is under this heading that it will be considered in Chapter 5.

The work on reactor development and isotope production falls under the general heading of "research into all aspects of atomic energy". It is essentially applied atomic research, though it arises from, and in turn gives rise to, much fundamental research. There is in addition a very important block of research work directed towards the long-range possibilities of atomic energy and the application of the new tools to fundamental science.

A large part of this type of research is concerned with the structure and properties of the atomic nucleus. One very profitable way to examine the nucleus is to bombard it with high-speed particles and see what happens both to the target and to the projectiles. A first concern, therefore, of the nuclear research worker is to provide himself with machines that will generate streams of particles of the right kind and having the right energies. A pile like Bepo or Gleep is

one machine of this sort, generating as it does a copious stream of neutrons, but other kinds of machines are needed to provide fast, charged particles. Several such machines, which accelerate electrons and protons to speeds approaching the speed of light, have been built at Harwell. These so-called particle accelerators are described in Chapter 6. In addition to these nuclear physics experiments, there are experiments concerned with the effects of radiation upon assemblies of atoms: that is upon the macroscopic structure of matter. The chemists too are interested in the effects of radiation upon matter, but from the point of view of the changes produced in its chemical properties, and of the effects upon chemical reactions. Other investigations in chemistry include studies of the chemistry of the heavy elements and of processes such as ionic exchange. These and other fundamental researches are discussed in Chapter 8.

In addition to the work described above there are two ancillary programmes which have almost universal application within the project. These are the protection of health and the development of electronic measuring equipment. The radiations from radioactive substances, if they are intense enough, can seriously damage living cells. It is therefore of the greatest importance to protect all workers, in both research and production plants, from exposure to radiations of harmful intensity. To effect such protection requires first a knowledge of the fundamental causes of the damage and the amount of exposure necessary to produce it, and second a technique for measuring the amount of radiation in working areas to ensure that it does not exceed the safe limits. In Chapter 7 an account is given both of the precautions taken to guard the health of the Establishment, work which is in the hands of the Medical and Health Physics Divisions, and, briefly, of the monitoring devices developed by the Electronics Division. It is hoped to give a more detailed account of the electronics work in a subsequent account. In the same chapter a brief reference is made to the more fundamental studies of the effects of radiation on living cells, and of their applications for medical purposes, which are being made by the Medical Research Council's Radiobiological Research Unit.

The final chapter is devoted to an account of the arrangements for co-operation with universities, and for enlisting the aid of industry in development and production. At the end of the account there are appendices in which details are given of the Divisional organization of the Establishment, papers published by members of the staff, and other matters of general interest.

THREE

THE PRODUCTION PROGRAMME

ONE has only to begin to talk about a specific programme to be faced with the primary difficulty, that no one of the Harwell programmes is self-contained. For example, the pile development work for the production programme also contributes to the reactor programme; and the development of the chemical separation plant will bear upon the processing of nuclear fuels for future reactors. Inevitably the attribution of one piece of work to one programme rather than another will often be arbitrary, but it is hoped that the interrelationships of the various pieces of work will be clear from the narrative.

Under the heading "Production programme" is included the work for the production piles, and the work on the chemical process for separating plutonium from uranium. Because the building of the two Harwell piles, Gleep and Bepo, formed essential preliminary stages in the development of production piles (though these reactors have many applications outside the production programme) they will be described first. We shall then go on to the work for the Windscale installations and for the other problems of production. An understanding of these problems demands some background knowledge of the properties of nuclear reactors, and a short explanation has therefore been included in Appendix B to which some readers may like to refer at this stage.

The Harwell piles

The first reactor built at Harwell was the Graphite Low Energy Experimental Pile, colloquially known as Gleep. Construction was started in the autumn of 1946, only a few months after the Harwell site was taken over, and the pile operated for the first time on 15th August, 1947. Since then it has been in continuous use, most of the time running 24 hours a day.

Gleep is a slow neutron reactor using graphite as a moderator and natural uranium and uranium oxide as fuel. It was designed as simply as possible, so that a reactor could be quickly available at Harwell for experimental work. To this end the design power was limited to 100 kilowatts, so that no elaborate cooling arrangements would be necessary. A fairly full description of Gleep was published in December, 1950, and this is reproduced in Appendix B.

The pile is used entirely for experimental purposes, especially for testing materials by methods to be discussed later, although for a time it was used to produce radioisotopes. For isotope production, however, and for many experimental purposes, a pile having a stronger neutron flux was necessary, and for this reason the construction was undertaken of the second Harwell pile, generally called Bepo, for British Experimental Pile O. The design of this medium-powered pile is based on proposals made following studies at Chalk River during 1944

and 1945. The design was engineered during 1946 by Mr. (now Sir) Christopher Hinton and his staff at Risley and the pile was built under their supervision; it started up on 3rd July, 1948.

The main difference between Bepo and Gleep is that Bepo is designed to operate at a power of 6,000 kW. To achieve this operating power, the uranium is cooled by a stream of air drawn through the channels in which it lies. Although Bepo is rated at sixty times the power of Gleep, it is little larger, a fact which may surprise those who expect the volume of a power unit to go up roughly as its rating. The reason is this. The size of a nuclear reactor is decided primarily by the so-called critical mass, that is the mass of fissile material needed to make the reaction go; when the critical mass has been reached and the chain reaction established, the power generated depends only on the rate at which the reaction is allowed to proceed. This rate is limited by the maximum temperature at which the reactor may be operated, and hence by the rate at which the heat generated is removed.

A description of Bepo was published in April, 1951, and this too is reproduced in Appendix B. Bepo is primarily an experimental tool, but there is also provision for making radioisotopes, which are an important by-product. The application of the pile to fundamental research will be discussed in Chapter 8 and its use for isotope production in Chapter 4. Its other main use is in the study of the effect of neutrons and γ-rays on materials, particularly those for use in the Windscale piles and power reactors.

It was never intended that Bepo should be a prototype power reactor; nevertheless a scheme is proceeding for extracting some of the heat generated and using it to warm laboratory buildings. An earlier scheme was abandoned because the space which had been set aside for the necessary equipment was used to house a dust filter as an additional precaution against the smallest chance of a health hazard from radioactive dust in the cooling air discharged from the chimney. In the new plan, the first part of which was ready for the winter of 1951, a conventional heat exchanger in the exhaust cooling air duct supplies hot water for space-heating neighbouring laboratory buildings.

Bepo has been running at high power for over three years now; as a result of the experience so gained an improved uranium cartridge has been designed which is capable of withstanding a higher temperature than the type at present in use. When cartridges of the new design are loaded into the pile, the higher permissible operating temperature will make it possible to increase the power output of the pile above the design figure of 6,000 kW.

Work for the Windscale piles

Having obtained an idea of the characteristics and capabilities of the two experimental reactors at Harwell, we can turn now to consider the Establishment's share in the design of the Windscale production piles. Obviously an important part of this contribution has been simply the experience of building a graphite-moderated pile, the acquisition of what is often called by the distasteful name "know-how". In addition both piles are being used to test the suitability of

materials for Windscale, to check the performance of ancillary equipments, and to develop operating procedures.

The need to test all kinds of materials used in a pile is dictated by two considerations, viz., the effect upon the pile of quite small variations in nuclear properties of materials, and the considerable changes in macroscopic properties produced by irradiation. It will be more convenient to consider the second of these in the chapter on reactors, but a word must be said about the first here.

To the nuclear engineer the most significant property of materials is the power to absorb neutrons, measured in terms of a quantity called the neutron absorption cross-section. It is shown in Appendix B that a pile is running at constant power when the neutron population is maintained at a constant value, dependent on the power level; in these circumstances the reproduction constant k is equal to one. But more neutrons are born in fission than are needed to maintain the reaction; the excess is absorbed in three different ways: usefully in substances being irradiated, wastefully but intentionally in the control rods, and wastefully but inevitably in the structural materials or the impurities which they contain or by leakage from the surface of the pile. Clearly this wasteful loss of neutrons must be kept to a minimum so that as many as possible can be usefully employed. It may be remarked in passing that the nuclear engineer generally speaks of "spare k" as a measure of the fraction of useful neutrons in a pile; it is of course his aim to keep the amount of "spare k" as large as possible.

Although the neutron cross-sections of many pure materials are quite low, it requires only a very small quantity of some impurities to increase the cross-section to a value far beyond that which can be tolerated for pile use. For example only one part in ten thousand (0.01 per cent) of boron in aluminium would nearly double its absorbing power. Indeed some impurities are harmful in concentrations so low as to make their determination by chemical analysis a difficult matter. They can however readily be detected by their effect on the reactivity of a pile, and since it is usually less important to know what the impurities are than to know what the effective cross-section is, a pile can conveniently be used to check the purity of sample materials. In the Windscale programme Gleep has often been used for this kind of test. The sensitivity of a pile for this purpose is remarkable; for example, less than one part per million of boron in graphite can easily be detected in Gleep. More will be said of the method of making these measurements in Chapter 8.

Another important research contribution to the production programme has been in the development of improved uranium cartridges. It may appear strange that any great amount of research is necessary to develop so simple a structure as a rod of metal enclosed in an aluminium can, but a little consideration will show that this simplicity is more apparent than real. In the first place uranium is a metal about which comparatively little was known, so that the preparation of sufficiently pure metal, and its fabrication into rods which could be accurately machined, called for a great deal of chemical and metallurgical research. Then there was the problem of fitting the rods with a can of aluminium, and sealing its ends, in such a way that there were no holes through which radioactive fission products could escape and that there was a good contact between the can and

every part of the surface of the rod, in order to ensure that the heat generated could be removed without the uranium getting too hot. This latter problem, as well as involving metallurgical research, required a method of determining how good was the thermal contact after the can had been sealed. A method of making this conductivity measurement was devised by the Engineering Division at Harwell and developed by them into a routine test procedure for use in a production plant.

Removal of heat from the bar posed many questions besides those concerning the thermal contact between slugs and cans. The design chosen for the cooling channels through the graphite is one of many compromises; on the one hand the channels must be large enough to allow a sufficient air flow without requiring a great deal of pumping power, whilst on the other hand they must not be so large as greatly to decrease the average graphite density and cause serious loss of "spare k". The theoretical design of such a channel is subject to many uncertainties and experimental tests of the calculations are essential. These tests were made in the Engineering Division, where a section of a single channel was erected, containing special cartridges equipped with fine thermocouples for temperature measurement.

The importance of chemical research in the development of piles, as distinct from the separation of fissile material, is perhaps not as obvious as that of research in physics or metallurgy. Nevertheless a great deal of work has been done by the Chemistry Division at Harwell in various directions. In the first place the need for materials of high purity has demanded the development of special analytical techniques especially for the determination of uranium, plutonium, and certain elements which are particularly harmful in the operation of piles. Then the chemistry of certain elements which had hitherto been of comparatively little importance because of their rare occurrence has had to be examined in far more detail; this includes many of the elements in the middle of the periodic table, especially the rare earth elements which occur among the fission products. Another problem confronting the chemist has been the chemical behaviour of graphite and carbon at comparatively high temperatures and in the presence of high intensities of radiation. For example, how much of the graphite will be oxidized in the pile? If this quantity were considerable the design would be complicated by the need to allow for a decrease in the amount of graphite with time. Fortunately the chemists were able to give a reassuring answer on this point.

An interesting problem which has confronted the physicist has been to devise a method for detecting burst cartridges. It is possible that, in the conditions in which they operate inside the pile, the aluminium cans enclosing the uranium slugs will occasionally rupture. It is very important that such a failure shall be detected before it is more than a trivial crack and before any radioactive material is discharged into the cooling air. Various methods for detecting the existence of pin-holes have been studied and a machine has been developed which will ensure that a failure can be detected at this early stage. Filters in the outgoing air provide a second line of defence.

The Establishment has also collaborated with Risley in the theoretical work and calculations required in the Windscale pile design. Before a pile is built it is

necessary to work out not only the optimum arrangement of the uranium and graphite lattice, but also the distribution of neutron flux throughout the structure, so that the performance can be foretold as accurately as possible. Other constants of the pile have to be evaluated theoretically in connection with the design of control and safety systems, which is by no means simple. These include particularly the pile period (the rate at which its power output responds to a change in conditions), a knowledge of which together with the neutron flux is required before the size and speed of operation of the control rods can be decided. On the practical side the operation of the control of safety rods demands the production of elaborate apparatus, with electronic control gear, to ensure that they may be moved at the right speed and within very fine limits. The use of these controls depends of course upon an accurate knowledge of the neutron flux in the pile, and this is obtained by means of ionization chambers, placed in the core, which feed electronic amplifiers and scalers. Most of the electronic equipment required for these purposes in the Windscale piles has been designed and developed in the Electronics Division at Harwell.

The construction of even so apparently simple a structure as the external or "biological" shield is not merely a matter of piling up concrete to a size that looks about right; calculations are necessary to ensure that there is at all points sufficient, but not too much, shielding. The decision as to what constitutes sufficient shielding depends upon a knowledge of what are called permissible tolerance doses of radiation; this however is part of a wider subject which is discussed later. When the calculations have been made and the shield erected it is still necessary to ensure that practice agrees with theory and that accident does not vitiate calculation, by measuring continuously the level of radiation in the neighbourhood of the piles. This is done by means of radiation monitors connected to electronic scaling and registering units. Monitors for Windscale were designed by Harwell and are now being manufactured by industrial firms.

The chemical separation process

We must turn now from the design of piles which produce plutonium to the extraction of the plutonium that they produce. Plutonium is a radioactive metal of fairly long life which is created atom by atom from uranium 238 by the absorption of a neutron followed by two successive beta decays([1]). The plutonium is distributed throughout the uranium slugs in very low concentration and the problem is to separate it in a pure state from the fission products and from the very much larger quantities of uranium; it is also desirable to recover the uranium so that it may be used again. Because they are different elements with different chemical properties, the separation of plutonium from uranium is easier than the separation of two isotopes of the same element, such, for example, as uranium 235 and uranium 238. Nevertheless it is still a very complicated process. The

([1]) The reactions may be written: $U^{238} + n^1 \longrightarrow U^{239}$
$U^{239} \longrightarrow Np^{239} + \beta$
$Np^{239} \longrightarrow Pu^{239} + \beta$

complexities arise from many factors: the very small proportion of plutonium present; the exceptional degree of purity required; but above all the extremely high radioactivity of all the material in the plant, and especially of the fission products. Plutonium itself is of course radioactive and also is extremely poisonous. Consequently every operation in the process must be done by remote control, with thick shields between the operators and the materials, and every conceivable leakage must be anticipated in the design. Such stringent requirements present the chemical engineer with difficulties probably greater than any he has had to overcome before.

Quite apart from the chemical difficulties of separating the fission products from the uranium and plutonium, there is the enormous physical problem of what to do with them when they have been separated. In a very short time the process engineers will have on their hands solutions containing hundreds of thousands of curies of activity, equivalent to hundreds of thousands of grams of radium. Such quantities of radioactivity had never been even imagined before the coming of atomic energy projects. It seems that the only way to deal with the situation is to concentrate the solutions in as small a bulk as possible and then store them somewhere until the activity has decreased to manageable proportions.

It can readily be imagined that for even laboratory-scale experiments on this process the experimenters must be particularly well protected against radiations and radioactive materials. Ordinary chemical laboratories are quite unsuited to the work and well-shielded cells elaborately ventilated are necessary. Such a laboratory takes a long time to build and some three years elapsed after Harwell was formed before the Chemistry Division had suitable, and sufficient, premises in which to carry on the programme of experiments in separation. Now the Division's "hot" laboratory is one of the most up-to-date in the world; it will be described in more detail in a later chapter. Until this laboratory was ready, however, work on the chemical separation process was done mainly at Chalk River in Canada. Indeed, the development of this process exhibits one of the best examples of the close collaboration between the British and Canadian projects. All the early work was done by a mixed team of British and Canadian chemists and chemical engineers at Chalk River, and the British sections of the team have been moved over to Harwell as laboratories and equipment have become available.

In addition to the separation of plutonium there is another separation problem, less complicated but still difficult: that of extracting natural uranium from low-grade deposits in the earth's crust. So far only quite rich deposits have been worked, but as the demand for uranium expands it will be necessary to work much lower grade deposits, and unless they can be worked cheaply and efficiently the application of nuclear energy to power production may never be economic. A mineral-dressing laboratory has therefore been set up in the Chemical Engineering Division with the main function of developing methods for the concentration of the uranium containing minerals of low-grade ores. This laboratory is mainly concerned with physical means of concentration, and works in close collaboration with two of the Department of Scientific and Industrial Research

establishments. These are the Geological Survey, which advises on all matters connected with the occurrence of minerals, and the Chemical Research Laboratory, which is responsible for research on the chemical processing of them.

Another important pile material which is the subject of research is graphite. There is a need for graphite having physical, and especially nuclear, properties which are better than those of the graphite in ordinary use at present. Much experimental work on this subject is being done by industrial firms under contract to Harwell, but small-scale plant has been set up in the Chemical Engineering Division so that experimental samples can be manufactured there, and new methods and materials tested. The chemical aspects of processes leading to the production of graphite and related carbonaceous materials are under investigation in the Chemistry Division.

FOUR

THE ISOTOPE PROGRAMME

ONE of the most widely publicized aspects of work on atomic energy, both in this country and abroad, is the use of radioisotopes, especially in medicine. Every newspaper reader is today familiar with tales of isotopes rushed to hospitals, of isotopes used in industry to determine wear in pistons or to control the dyeing of fabrics, even of isotopes used in sport to locate elusive golf balls. In fact the production of such isotopes is essentially a by-product of work on atomic energy and more or less incidental to the operation of piles, but because their application in research was already understood, immediate advantage could be taken of the vastly increased scale, and range, of production made possible by nuclear reactors. At Harwell their production was one of the first applications of Gleep and is now an important charge on the "spare k" of Bepo. However, before discussing Harwell's work in detail it may perhaps be as well first to define the meaning of the word "isotope".

What is an isotope?

The nucleus of an atom is built up of protons and neutrons. In all the atoms of a given element, the number of protons in the nucleus is constant; it is called the atomic number and it determines the chemical properties of the atom. With this fixed number of protons there may be associated a varying number of neutrons. This means that all the atoms of any particular element have the same chemical properties, but their masses may differ (because the mass of an atom is equal, approximately, to the sum of the masses of the protons and neutrons in the nucleus). These different forms of the same element are known as isotopes of the element. The isotopes of one element differ from one another in their physical, not their chemical, properties. Some isotopes are stable; the differences between them are solely those arising from the difference in mass, for example different amounts of bending in a magnetic field, different rates of diffusion, etc. Other isotopes are radioactive, that is their nuclei break down spontaneously and emit particles or electromagnetic waves, or both; radioactive isotopes differ from one another in, for example, the type and energy of the particles they emit, and in their half-lives. At least one radioactive isotope is known to exist for all known elements. The two features of radioactive isotopes that give them their technological importance are that they are indistinguishable in their chemical properties from the stable isotopes of the same element, and that they emit radiation which can be detected by various means, such as photographic films, electronic instruments like Geiger-Müller counters, and the scintillations produced in certain phosphors and organic crystals. In this way they can be detected in the presence of considerably larger quantities of stable atoms of the same element, by methods

which ordinarily do not require any interference with the substance in which the atoms are embedded. Stable isotopes, on the other hand, differ from one another only in the masses of their atoms; the presence of a small quantity of one isotope among a large mass of another can be determined by instruments like the mass spectrometer, but the process is somewhat complicated and requires that the specimen should be obtainable in a form suitable to the instrument. Nevertheless there are experiments for which stable isotopes have decided advantages over radioactive isotopes.

Harwell's work in the isotope field is concerned with both production and application in research. Although some radioisotopes occur in nature, most of them are made artificially, by bombarding stable elements with neutrons, protons or deuterons (nuclei of the heavy hydrogen atom). For the production of isotopes formed by neutron bombardment the nuclear reactor is obviously supreme, since it generates neutrons in far larger quantities than any other device. We shall therefore be concerned mainly with reactor-produced isotopes in this account. It must not be forgotten, however, that a few important radioisotopes can only be made by accelerators like the cyclotron.

The production of radioisotopes in piles

There are three main groups of nuclear reactions by which radioisotopes are produced in the pile; each begins with the absorption of a neutron but the subsequent course of events varies. In the first group the irradiated material captures a neutron to form a nucleus one mass unit heavier, which gives off γ radiation after a very short interval and yields a radioisotope of the parent substance; these are therefore known as (n, γ) reactions. As an example, radioactive sodium 24, which is much used in tracer studies of the blood, is formed by this reaction from the stable isotope, sodium 23. Some γ-emitting isotopes formed by the (n, γ) reaction are used for radiographic purposes—for example cobalt 60—and for these particularly the reaction has the great advantage that, when their activities have decayed, the samples can be returned to the pile and warmed up, so to speak, again and again. A disadvantage of the (n, γ) reaction is that the product isotope is chemically identical with the parent and therefore cannot readily be separated from it, as a rule. However, in (n, γ) reactions on elements in certain compounds the emission of the γ quantum in the reaction causes the nucleus from which it is emitted to recoil with sufficient energy to break the bonds that hold the recoiling atom in the chemical compound in which it was before irradiation. The classic example of this reaction, first reported in 1934 by L. Szilard and T. A. Chalmers, after whom it is called, occurs in the slow neutron bombardment of ethyl iodide; some of the iodine atoms are changed by an (n, γ) reaction to iodine 128 and these atoms are thrown out as free radioactive iodine and can be separated chemically from the target compound.

Where it is necessary to have an isotope which is "carrier free", that is, where most of the atoms present are radioactive, transmutation reactions are used. These form the second group spoken of above, and are of the kind in which the element bombarded changes (i.e. is transmuted) into the element required. An

example is the production of phosphorus 32 from sulphur 32; the nucleus of sulphur first captures a neutron and then ejects a proton and so is transmuted into phosphorus, the element below in the periodic table. This reaction is usually called an (n, p) reaction; another of the same general kind is the (n, α) reaction, in which the ejected particle is an α particle. Such reactions generally require fast neutrons and so are performed in the core of the pile where the flux of both fast and slow neutrons is greatest. An important exception is the reaction by which tritium (the hydrogen isotope of mass 3) is formed from lithium; this requires neutrons of quite low energy (0.04 MeV).

The third main group of nuclear reaction is that in which, after neutron capture, the newly formed isotope of the irradiated element decays to the element required. Iodine 131, for instance, is formed by irradiating tellurium 130, which absorbs a neutron to become tellurium 131; this decays to iodine 131 with the emission of a β particle. The reaction is written

$$\mathrm{Te}^{130}\,(n, \gamma)\,\mathrm{Te}^{131} \longrightarrow \mathrm{I}^{131} + \beta$$

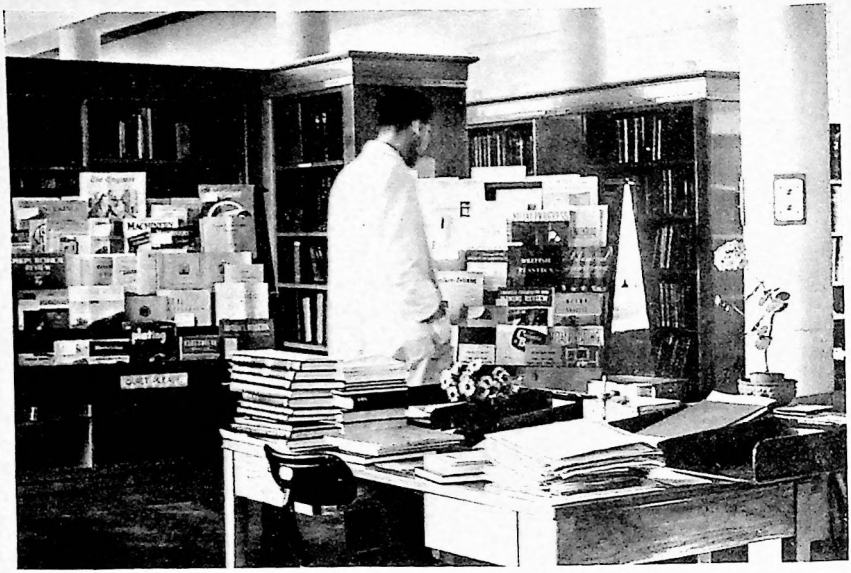
The iodine so formed can be extracted from the tellurium and obtained carrier-free.

In the isotope manufacturing process the class of reaction selected will depend upon the isotope wanted and, in some degree, on the extent to which it must be carrier-free. It is then necessary to decide where the sample is to be placed in the pile whilst it is being "cooked". One factor to be considered is the kind of reaction desired; reactions like (n, p) and (n, α) which require fast neutrons will have to take place in the central core of the pile. (n, γ) irradiations, on the other hand, are sometimes carried out in the reflector, where use is made of the slow-neutron flux that would otherwise be largely wasted. A second factor is the required specific activity, that is the radioactivity per unit mass of the final product; high specific activities require strong neutron fluxes and therefore irradiation in the core. In all this it is of course necessary to bear in mind the amount of "spare k" available, which is usually about 1 per cent. Since substances are usually irradiated in compound form, allowance has to be made for the absorption by impurities and by other elements in the compound beside that of the wanted element, and a suitable choice is important. Chlorides, for example, are highly undesirable, as chlorine readily absorbs neutrons.

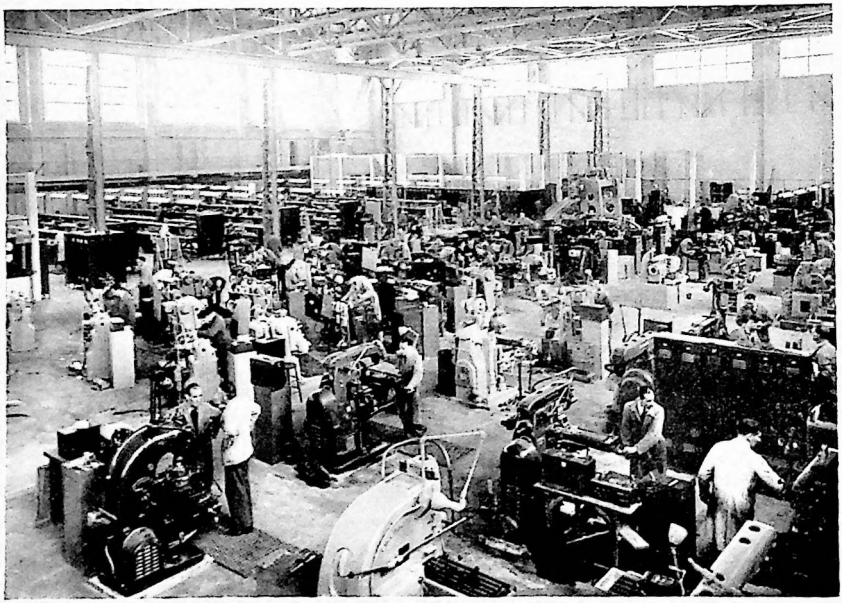
The method of irradiating samples at Harwell is quite simple. A quantity of the sample, usually in the form of a metal or salt, is weighed out into a cylindrical can, which is then placed in a graphite block and pushed into one of the "isotope holes" in Bepo. The graphite blocks are inserted and removed through a massive lead tunnel and transported in lead or steel containers to protect the operators against radiation. Normally samples are loaded into the pile each Monday and they are irradiated for some multiple of a week. If an irradiation is for a short period only the sample is shot into and out of the pile with pneumatic equipment. The sample and can are both active when removed from the pile, and have therefore to be handled from a safe distance by means of remote handling equipment. Radiation monitors are used as routine precautions against damage to the operator's health.

1. The main-gate, Harwell.

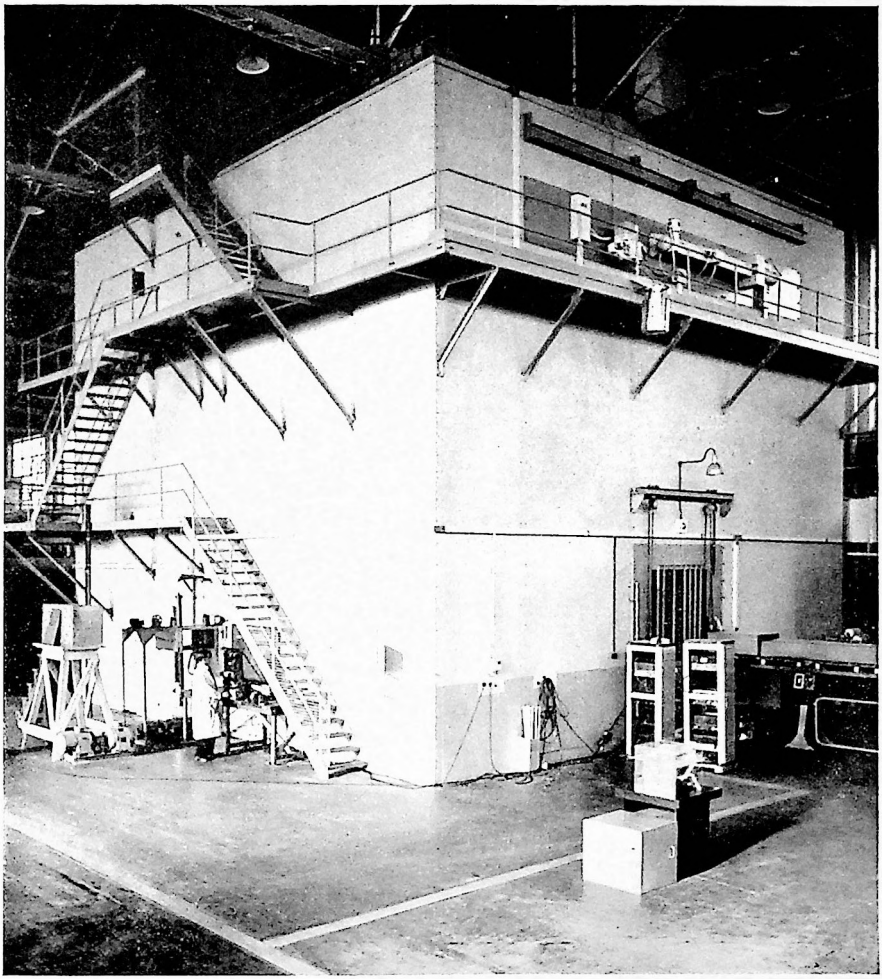
2. Staff clubs, hostels, and houses outside the Establishment.



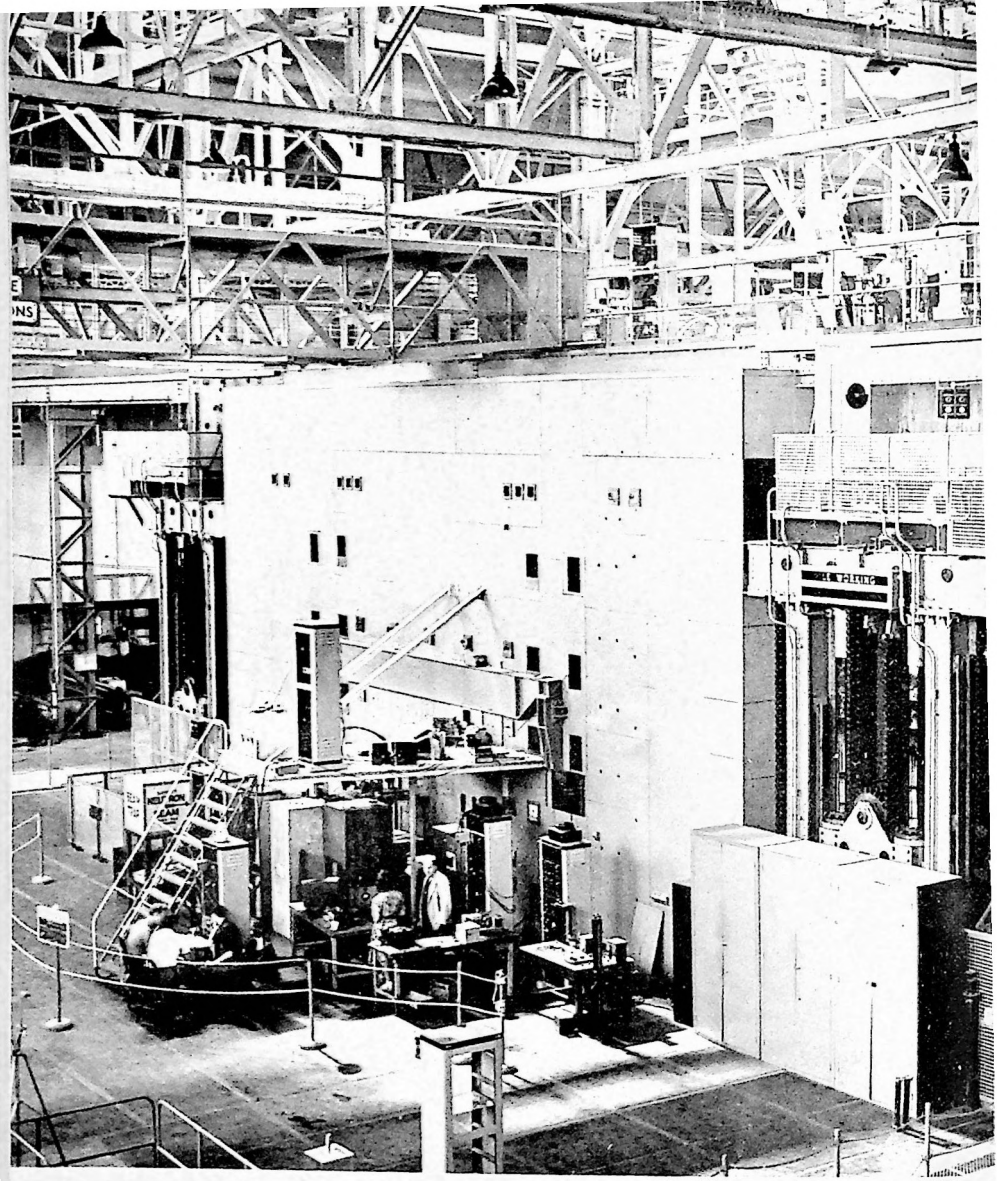
3. A corner of the extensive library.



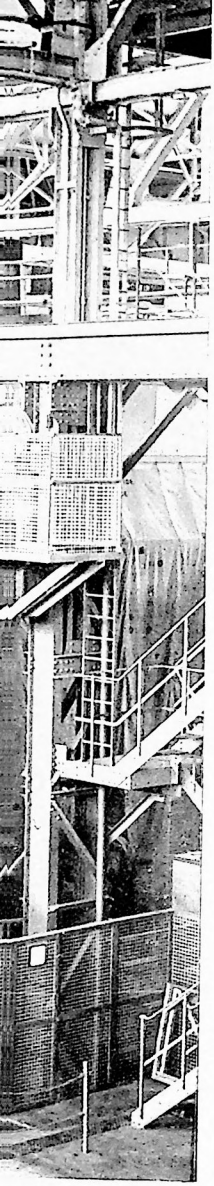
4. Part of the main workshops in one of the hangars.

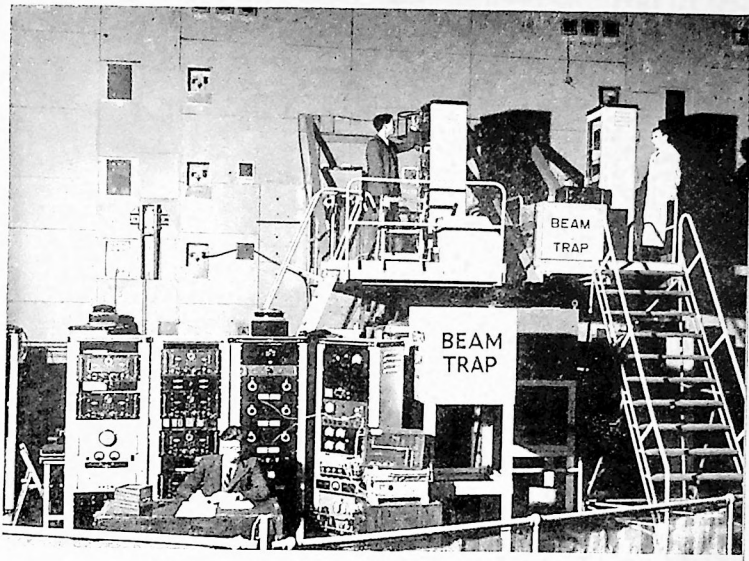


5. The low-power pile Gleep built inside one of the hangars. The operator at the left-hand face is using the pile oscillator to measure the nuclear cross-section of a sample; behind the operator, on a wooden stand, is a beam trap, to stop neutrons emerging from the hole in which the oscillator moves. The dark rectangle on the right-hand face is a screen covering the thermal column. Above it, on the gallery, can be seen some of the servo-mechanisms which operate the control rods. Protruding from the roof of the pile, above the gallery, is the short exhaust stack. The cylindrical object hanging from the gallery is an ionization chamber which monitors the air of the hangar to ensure that there is no excessive beta radiation.



6. Bepo, the larger of the Harwell piles. In the centre is the "experimental" face surrounded by counting and other experimental equipment; experiments are also made at the top of the pile, where equipment may be seen. In the upper right-hand picture is a close-up of this face. The dark rectangles on the pile face are the holes, normally blocked up, from which neutron beams may be allowed to emerge. The "beam traps" are blocks of concrete, which absorb the neutron beams after use. The lower right-hand picture is a view of the pile control-room.

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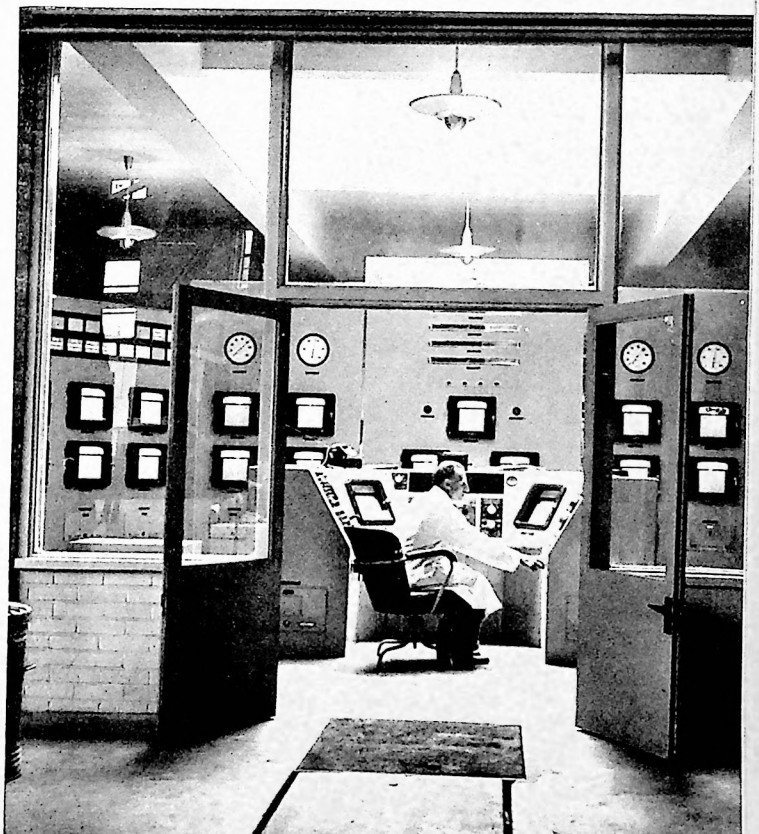
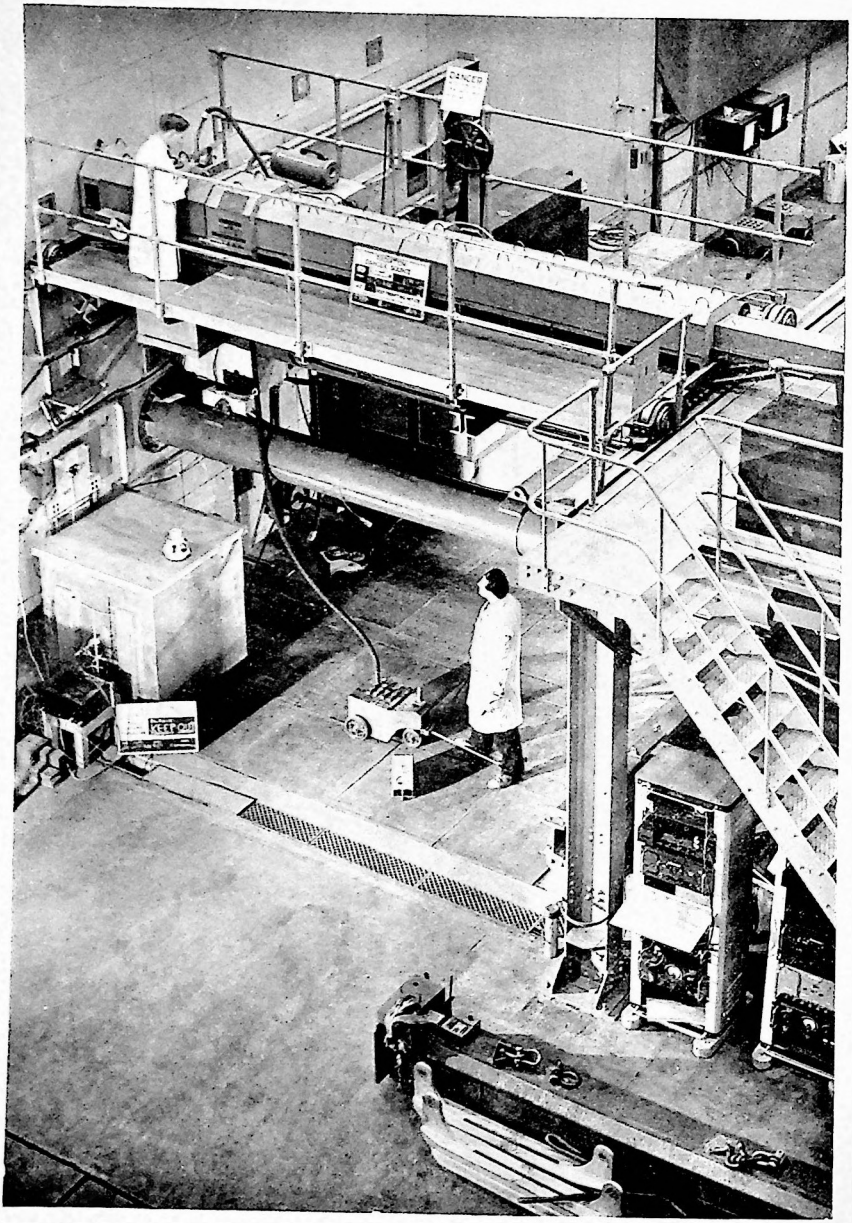
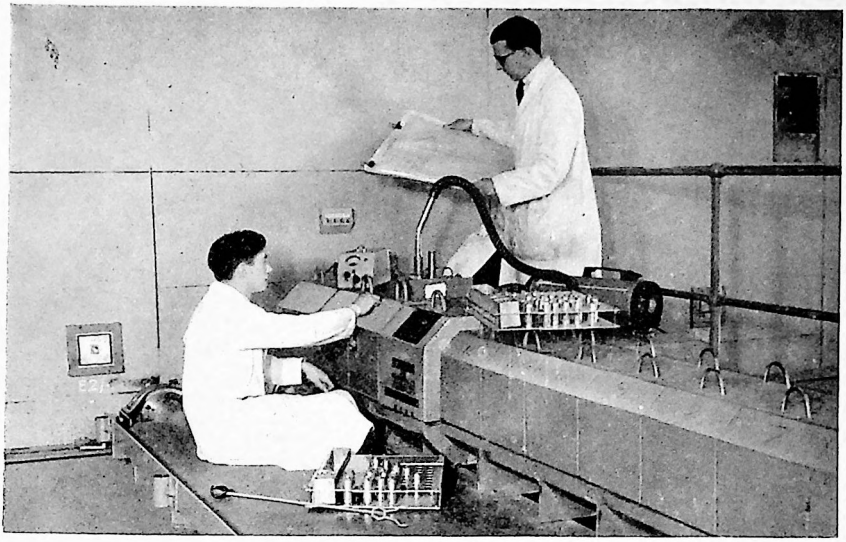
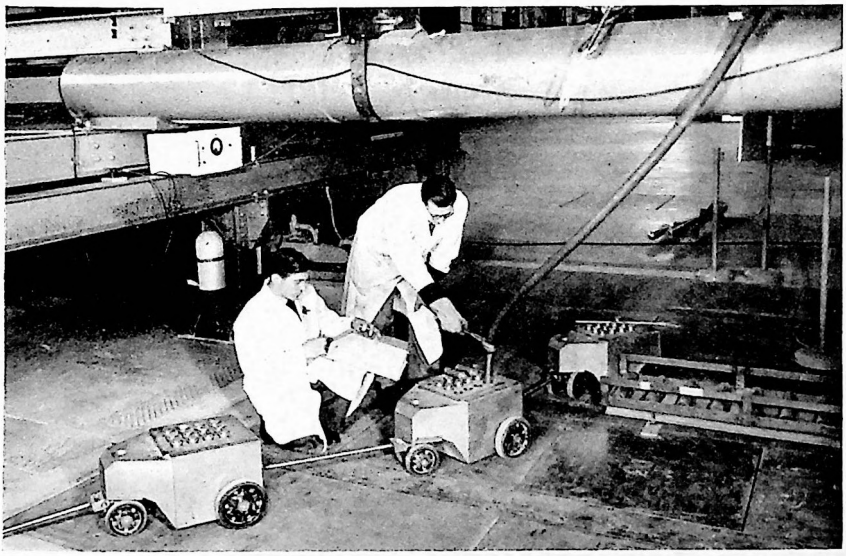




7. Radioactive isotope production in Bepo. The material to be irradiated is placed in small aluminium cans, which are in turn placed in graphite blocks and slid into the pile. After irradiation the graphite blocks are withdrawn into the lead tunnel (on the platform) and the cans automatically discharged through flexible tube into the lead-shielded truck below.

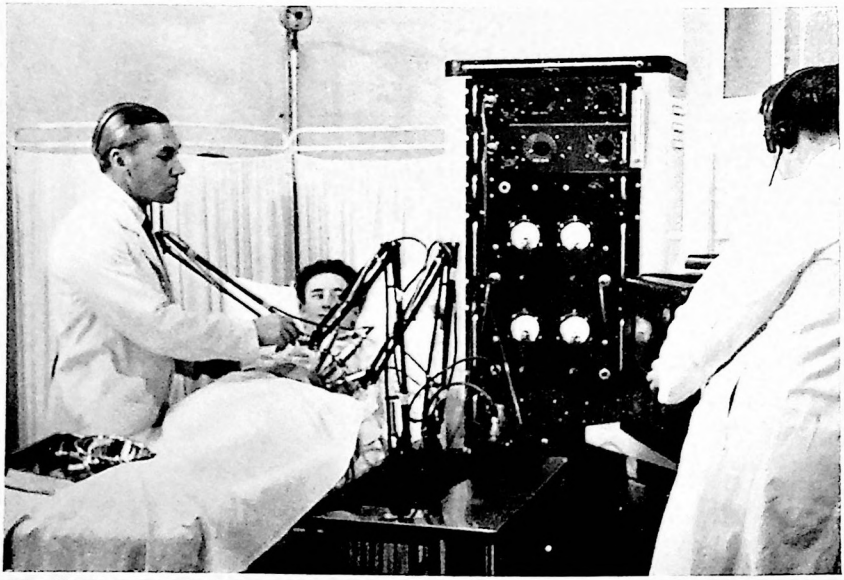


8. Isotope production in Bepo: a close view of the equipment on the platform in Plate 7. Two trays of cans awaiting irradiation can be seen in the middle of the picture. The flexible tube for extracting irradiated cans is sticking up from the lead tunnel.



9. The use of handling tongs and portable monitors is exemplified by this picture, which shows an operator placing the delivery tube (in the isotope unloading equipment of Plate 7) in a shielded truck, to collect isotope cans. A second operator is pointing a monitor at the active equipment.

10. Loading a can of a short-lived isotope into the wing of an aircraft for speedy delivery to South Africa.



11. Plastic surgery: a plastic surgeon is using radioactive sodium to determine whether the blood is circulating in a skin graft, and hence whether it is safe to go on with the next stage of the operation.

The activity of an isotope produced depends on the intensity of the neutron flux, the fraction of neutrons absorbed by the element in question, the half-life of the radioisotope required, and the bombardment time. An "isotope calculator", working on the slide-rule principle, has been devised at Harwell which takes into account all these factors and enables an estimate to be made very simply of the activity a sample will acquire in given conditions.

In addition to controlled irradiations in the pile, there is a prolific source of radioisotopes in the fission products resulting from the fission of the uranium. Some thousands of curies of fission products, all of elements near the middle of the periodic table, are formed in this way every day, and from these fission products particular elements can be extracted by chemical methods. A great deal of research has been done in the Chemistry Division on these extraction processes. These experiments, in agreement with earlier American work, have shown that ion exchange columns, working on the same principle as the domestic water softener, are admirably suited to the purpose. By proper arrangement of a column it is possible to separate nearly all the important fission products of life longer than a few days. In particular all the rare earths from lanthanum to holmium, with the exception of samarium, can be completely separated and recovered. Manipulation of the equipment is simple, a matter of considerable importance when all operations have to be performed by remote control from behind radiation shields.

Processing irradiated material

The material put into the pile may be either an element or a suitable chemical compound containing atoms of the element it is desired to bombard. Sodium 24 for instance is obtained by the (n, γ) reaction on the sodium 23 contained in sodium chloride or carbonate; phosphorus 32 on the other hand is obtained by irradiating large blocks of sulphur, from which it is formed by an (n, p) reaction. Often it is found necessary to remove the radioisotope from the target material by chemical means and much experimental work has been done both in the Isotope and Chemistry Divisions and at the Radiochemical Centre on suitable extraction methods. The chemical manipulations are frequently complicated, mainly because the proportion of wanted isotope present is extremely small and because the final product must be very pure, and often medically sterile. The isotopes must therefore be analysed spectrographically to control the amount of chemical impurities in them and they must be compared with a standard to determine their radioactivity. Thus it is desirable to standardize the extraction processes as far as possible and to produce the active isotopes in certain forms only. Phosphorus 32, for example, is dispensed as orthophosphoric acid and iodine 131 usually as an iodide. If the user wants them in some other compound than that dispensed he can synthesize the desired compound from the known composition of that supplied by Harwell, or this can be done at the Radiochemical Centre at Amersham.

This Centre was administered by Thorium Limited, under contract with the Ministry of Supply, up to 1st April, 1950, when it became the direct responsi-

bility of Harwell. So far the main work of the Centre has been the processing and distribution of natural radioactive substances, principally radium and radon, for therapeutic and radiographic purposes. The Centre is, however, doing much work on the synthesis of compounds containing radioactive atoms. Already it can offer quite a wide range of compounds of this type, particularly those containing carbon 14, which are of great importance as radioactive tracers in biological research. A complete list of available radioisotopes and their compounds, and also stable isotopes, is included in a priced catalogue issued by Harwell.

Harwell also undertakes to irradiate customers' own samples in certain circumstances. Generally it is not expected that these special irradiations will require any chemical or other processing. It is necessary for the Establishment to know the reason for every irradiation because it often happens that the desired result cannot be achieved by the method suggested by the enquirer. In particular the effect of nuclear recoil in changing the nature of the product is often overlooked.

Distribution of radioisotopes

After a radioisotope has been removed from the pile and suitably processed, it has to be transported to the user, who may of course be at the other side of the world. The radioactivity of these products raises unique problems of packing and shielding. The shielding needed varies from one isotope to another; carbon 14, for instance, emits such a soft β radiation that it cannot penetrate even the glass tube containing the isotope, whereas iodine 131 emits γ-rays as penetrating as strong x-rays and has therefore to be placed in a thick-walled lead container. Much thought and ingenuity has been expended on the design of containers which will provide adequate shielding and at the same time will not be excessively heavy, so that the ordinary postal, rail and air transport facilities may be used, without any health hazard to those handling the package or any harmful effect on photographic plates in neighbouring parcels. Where speed is necessary, as in transporting radioisotopes of short half-life, road and air transport are preferred to rail and sea. One method of air transport, first suggested by the South African Council of Scientific and Industrial Research, uses the fact that the intensity of radiation falls off rapidly with distance from the source (as the inverse square, in fact). If isotopes like sodium 24 are placed in the wing-tips of large aircraft, their radiations are so much reduced at the fuselage that they can hardly be detected, even although no heavy shielding is placed round the isotope. By this means the cost of air transport is very greatly reduced.

The production of radioisotopes first began at Harwell in September, 1947, using Gleep; it was transferred to Bepo in February, 1949. Since that date the scale of operations has increased enormously and the Establishment is now able to supply many of the isotopes of long life which two years ago could only be bought from the United States, as well as those of shorter life. A steadily increasing proportion of the production is exported; overseas customers include Argentina, Australia, Austria, Ceylon, Denmark, Finland, France, Germany, Holland, Hong Kong, India, Ireland, Israel, Italy, New Zealand, Norway, Pakis-

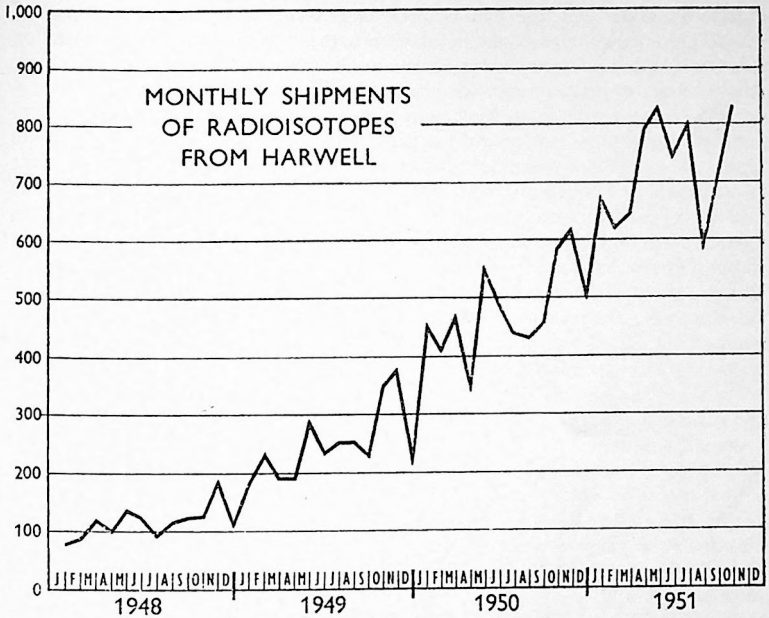


Fig. 1. Graph of isotope production at Harwell.

tan, Portugal, South Africa, South-West Africa, Spain, Sweden and Switzerland. The rate of growth in production is shown in the accompanying graph; at present deliveries are on the scale of 800 a month.

Applications of radioisotopes

By far the greatest number of applications of radioisotopes has hitherto been, and probably will continue to be, to research (medical, academic and industrial), although there is an increasing use in medical therapeutics and in industrial processes. The functions of isotopes in these applications fall into three main groups. In the first, the tracer method, the radioactive isotope is employed to trace the movements, or determine the whereabouts, of larger quantities of its stable isotopes. In the second, use is made of the ionizing effect of the radiations from radioisotopes. In the third group the absorption or scattering of the radiations from isotopes is made to give information about the objects which do the absorbing or scattering. The tracer technique, as well as being more widely applied than the others, is one of the oldest, having first been used (with naturally-occurring radioactive materials) as early as 1912.

Radioisotopes have been applied more extensively in biological and medical investigations than in any other field. Their uses for these purposes are based on the fact that a biological organism cannot distinguish between a radioactive element and its non-radioactive counterpart, since the two are chemically identical. Therefore, if somebody drinks or has injected into him a solution containing a radioactive isotope (for example radioactive iodine 131), mixed with its stable, naturally-occurring isotope (in this instance iodine 127), the active and inactive isotopes will follow exactly the same paths in the body. But the location of the radioactive substance can readily be determined by the effect of its radiations on suitable detecting instruments, and since whatever happens in the body to the iodine 131 also happens to the stable iodine, the fate of the latter can be established. In this instance, the iodine goes to the thyroid gland, which is the chief storehouse of iodine in the body, and much of our understanding of the functions of this gland, and of the effects of certain drugs upon it, has been obtained with the help of radioactive iodine; thus tracer experiments with iodine 131 showed that iodine in iodides is converted by the thyroid to thyroxin and that the latter is the thyroid hormone. Moreover, this particular tracer application of iodine 131 is used in the diagnoses of diseases of the thyroid; by means of a suitable Geiger counter the shape of the gland can be traced quite accurately and, if the intensity of the radiation is measured, an indication can be obtained of the rate at which iodine is taken up by the gland. If there is an advanced cancer of the gland and fragments of the diseased tissue have broken off and moved to other parts of the body, they can be located by the radiations and excised surgically.

Another interesting application of radioactive tracers to medical diagnosis is the use of sodium 24 to determine the rate of flow of blood, for example when it is suspected that there is restriction, as in thrombosis. Suppose a Geiger counter is placed on the patient's hip and an active sodium chloride solution injected into a vein in his foot; the interval of time that elapses between the moment at which the injection is given and that at which the counter begins to respond, indicating that blood containing active sodium is flowing in the hip, will show how long it has taken the blood to flow up the leg. If the time taken is so long, compared with the other leg, as to suggest that there is a constriction in the arteries, the position of this constriction can be found quite accurately by moving the counter down the leg. This principle can be extended to study the pumping action of the heart. Another active isotope, phosphorus 32, can be used to measure the total volume of blood in the body, by comparing the activity in unit volume of the blood with a standard sample suitably prepared. In another field, that of botanical and biological research, much new knowledge of photosynthesis in plants and of metabolism in cells has been obtained from tracer experiments with compounds containing radioactive carbon 14.

It has already been noted that in addition to their use for medical research and diagnosis, some radioisotopes have therapeutic applications: for example, the long-established treatment of tumours by γ-rays from radium. These therapeutic applications fall into the second of the general classes enumerated above, because they depend on the fact that the radiations produce ions in diseased

tissues and so destroy them. In some treatments diseased parts are irradiated from outside the body; the external source of radiations may be an x-ray tube, radium, or nowadays, a radioisotope like cobalt 60. Cobalt 60 is a strong γ emitter which has many advantages over radium, particularly that it is cheaper and emits much more homogeneous γ radiation and much softer β radiation which can easily be filtered out; also there is no danger of radioactive contamination from radon gas. It can, moreover, be machined to any desired shape or size before irradiation, or it can be drawn into thin wire; in this way radioactive sources can be tailored to fit any special needs. An alternative method of treatment is to take advantage of the property of preferential uptake, which we have already discussed in connection with iodine; thus if a patient is given a dose of a solution containing iodine 131 in much greater strength than that required for tracer use, the radiations from the great concentration of iodine which builds up in the thyroid will be absorbed in the diseased thyroid tissue and destroy it. Certain blood disorders have been treated with phosphorus 32, which is taken up preferentially by the bone marrow and there inhibits the production of red blood cells. A difficulty with this type of treatment is that it is essential that practically all the radioactive material shall be absorbed in the diseased tissue, as otherwise it will not be possible to get enough radioactive substance into the tumour to destroy the malignant cells without at the same time destroying normal cells elsewhere. Unfortunately, there are many conditions for which this necessary prerequisite cannot be satisfied, so far at any rate.

In another form of the treatment, encouraging results have been obtained with the mixed β and γ radiation from gold 198; the isotope, in the form of a colloidal preparation, has been injected into the tumour so as to irradiate it from within.

The study and development of the applications of radioisotopes to medicine are being energetically pursued by the Medical Research Council, in hospitals and research institutions throughout the country. Harwell's part is to supply the isotopes, and medical users, both in Great Britain and abroad, make up by far the greater part of the Isotope Division's customers. Phosphorus 32 and iodine 131 are produced in curie amounts, and weekly extractions of these, and sulphur 35, are made to meet normal requirements; in addition, special arrangements exist to provide supplies wanted urgently in emergencies. For therapeutic purposes pure β-emitting plastics of relatively high specific activity are being developed at Harwell; these will have the advantage that they can be put back into the pile after use and their activity restored.

In the industrial field radioisotopes have not hitherto been employed to anything like the same extent as in medicine and research. Nevertheless there have been several applications and interest is spreading; this has been stimulated by the field service and advisory organization set up by Harwell. The function of this organization is to examine the problems, whether of research or production, brought to them by industrial and other enquirers and to advise on the possibility of using isotopes to solve them, and on the choice of suitable equipment and isotopes to do the job; advice is also given on the health precautions to be observed in using the equipment. Where necessary the Division will perform tracer experiments at the enquirer's works, providing the equipment required in

addition to the isotopes. In this way small concerns which lack research staff are enabled to take advantage of this newest technique. The attention of the public was first drawn to this service in May, 1949, at the British Industries Fair, where the Establishment had a stand. This exhibit led to a considerable number of enquiries from industrial firms and to the development of several applications, especially of tracer techniques. Nevertheless the industrial use of radioisotopes is still small and there is no doubt that in many fields it could be much wider.

Some industrial enquiries have led to interesting tracer applications. For example, in connection with the manufacture of textiles, it is necessary to measure the thickness of an oil film spread over very thin nylon fibres. By mixing with the oil used in the process a small proportion of ethylene dibromide in which the bromine atoms are radioactive, it is possible to measure as little as 10^{-10} gram oil on a centimetre of fibre, by allowing the rays from the active bromine on the fibre to darken a photographic plate. In this way very small variations in the thickness of the oil film could be determined. In another investigation the wear of cast-iron bearings, when inadequately lubricated, was studied. The bearing metal was activated in the pile and then the bearing was allowed to run with various amounts of oil. The amount of metal worn off and washed away by the oil could be determined from the consequent radioactivity in the oil, even although it amounted to as little as 1/100,000 oz. in a quart of oil. Another problem is to discover the whereabouts of small leaks in underground cables in which gas is maintained at pressure to aid in the insulation. This is being solved by mixing with the insulating gas a radioactive gas such as methyl bromide in which the bromine atoms have been activated. The point at which the active gas diffuses from the interior of the cable can then be determined by means of a suitable counter. Other investigations have included the determination of the coefficient of diffusion of one metal into another and a study of the reasons for the uneven dyeing of fabrics.

An industrial application which falls into the second of the two general categories described, that in which use is made of the ionizing effect of the radiations, is the dispersal of electrostatic charges. These charges are formed by friction in certain industrial processes and may be a nuisance, or even a considerable hazard in processes where a spark might ignite an inflammable solvent or other material. The principle here is that charged particles ionize the air through which they pass, rendering it conducting and so allowing static charges on nearby objects to be conducted to earth; the idea is not new—polonium, a naturally-occurring α-emitter, was used for this purpose some time ago—but artificially-produced radioisotopes introduce a new flexibility into the application. One industry in which the formation of static charges presents an acute problem is paper-making, and several cases have been dealt with successfully by the use of β-sources like thallium 204, fixed at experimentally-determined positions on the machines. Other applications are being investigated experimentally, but so far most uses in this category are in medical therapy, as has already been said.

Several interesting methods of using the absorption of the radiations have been devised. One that was exhibited in the form of a working model at the British Industries Fair, and subsequently manufactured commercially under a

Ministry of Supply licence, is a device for measuring the thickness of materials continuously. It makes use of the fact that β-rays are attenuated on passing through absorbing material to an extent depending on the thickness of the material. In the model, a calcium 45 source was placed under a moving belt of paper, above which a Geiger counter was mounted; the counter was connected to a counting rate-meter which could be calibrated directly in terms of paper thickness, since the number of counts in unit time varied according to the thickness of the belt. The manufactured version of this equipment is arranged to register departures from a standard thickness since this is more useful in a manufacturing process than an absolute measure of the thickness. It should be remarked that "thickness measurement" is not a wholly accurate description; what is actually measured is the weight per unit area, which corresponds to the thickness when the product is uniform. Recently experiments have been made at Harwell on another thickness measurer, which like the first was originally described in America, in which use is made of the scattering rather than absorption of particles. When a stream of β particles falls on a metal, some of the particles will be scattered backwards in the direction from which they came, to an extent which depends, *inter alia*, on the atomic number of the scattering element. If the scattering material consists of a metal sheet covered with a thin layer of another metal, as for example in tinplate, then the amount of scattering will depend on the thickness of the layer and on the difference between its atomic number and that of the base metal; if this difference is fairly large the relation between thickness of layer and scattering will be nearly linear. In the experimental arrangement a source of β particles (thallium 204) was put on a ring inside an ionization chamber, on top of which was placed the plated metal; β particles from the thallium are scattered back into the ionization chamber and the resultant current gives a measure of the layer thickness.

Reference has been made to the use of cobalt 60 as a substitute for radium in radiotherapy. Gamma-emitting isotopes are also very suitable for radiography in industry, for such purposes as the examination of thick steel castings, and the preparation of artificial γ sources is an important feature of the isotope programme. Such sources have the advantages over radium and radon (which have been used in the past) that they are very much cheaper and, since they are made by (n, γ) reactions, they can be "warmed up" in the pile when they have decayed; some can be made with a higher specific activity than radium. The choice of isotope to be used depends on the energy of the γ-ray desired and also on half-life and specific activity. Sources, in standard sizes, are made at Harwell with three isotopes, iridium 192, tantalum 182, and cobalt 60, of which the last has the longest life. Each source is enclosed in aluminium alloy to stop β particles and the whole is placed in a lead container which is so designed that, when its plug is removed, a cone of γ-rays emerges from the centre. Used in this way a single object can be irradiated whilst preventing radiation in all other directions, without removing the source from its container. If the source is taken out of its container several objects can be irradiated simultaneously. These sources, being small and readily portable, can be used in many places where an x-ray tube will not go, for example inside narrow pipes or welded boiler tubes. Their low cost

permits their use for routine examinations in foundries and steel works, where the cost of radium or an x-ray set would be prohibitive. They are already in use in a number of works in this country and abroad.

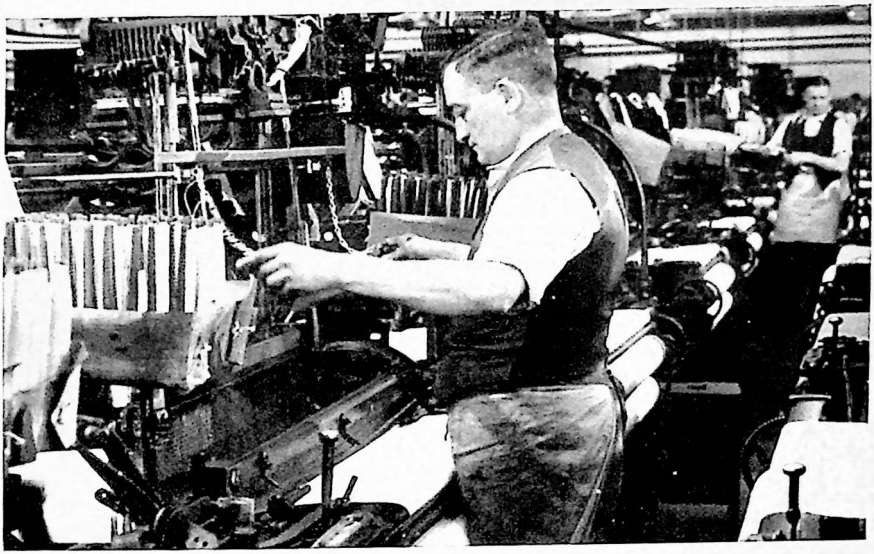
Stable isotopes

In some tracer studies stable isotopes have advantages over radioactive ones though the technique used is not as direct. The presence and amount of the stable isotopic tracer can only be determined by analysing the masses of the atoms of the element concerned in the sample. For this purpose an instrument called the mass spectrometer is used, and to operate this it must be possible to obtain a sample in the form of gaseous ions. Stable isotopes are used in two cases: where the radioactive isotope is not convenient, by reason of either too short or too long a half-life, or where radioactivity would have a harmful effect on an organism. For instance, the stable isotope carbon 13 would be preferable in some experiments to carbon 14, which has a very long half-life leaving undesirable radioactivity after the experiment, or to carbon 11, which has an extremely short half-life. Similarly, the radioactive isotopes of oxygen and nitrogen have very short half-lives, and the stable isotopes oxygen 18 and nitrogen 15 have to be used instead.

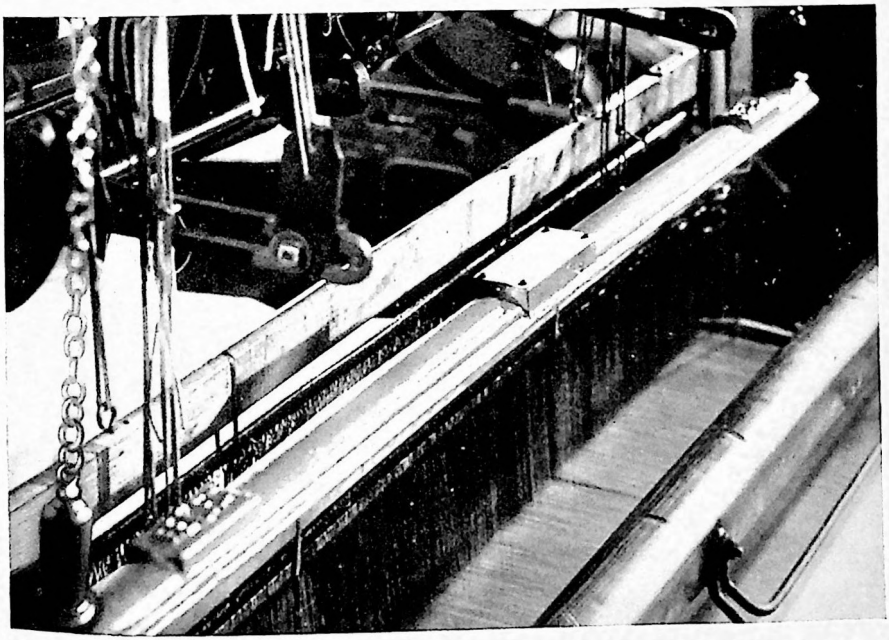
At Harwell the production of stable isotopes is being pursued by four methods. In the first the desired isotope is separated from the natural mixture by fractional distillation at low temperature. Natural carbon monoxide, a gas at normal temperatures, is cooled until it is in liquid form and then distilled in tall columns; the distilled product consists of carbon monoxide gas in which 65 per cent of the carbon atoms are carbon 13 and about 5 per cent of the oxygen atoms are oxygen 18. From this, barium carbonate containing the carbon 13 and water containing the oxygen 18 are prepared. A second method depends on the difference in the rate at which isotopic atoms of different masses diffuse in a gas in which a thermal gradient is maintained. This plant, which is not yet in operation, will produce oxygen whose content of the isotope of mass 18 will be enriched one hundred times normal.

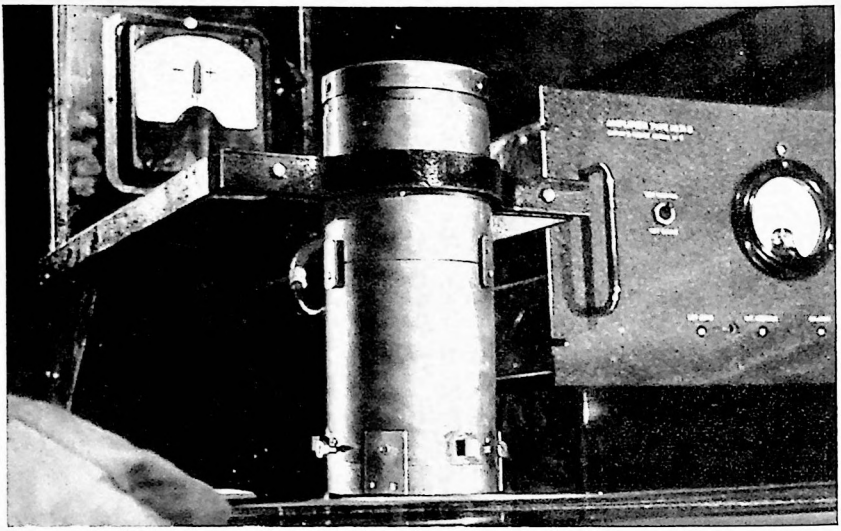
The third method is the electromagnetic separation method. The principle was first used by Aston in Cambridge in 1919 for his mass spectrograph, and it was developed on the large scale in America during the war to separate uranium 235 from uranium 238, for one type of atomic bomb. In this method ionized atoms of the natural element are accelerated in an electric field and then sorted by their masses, by means of a magnetic field. In this way beams of ions are obtained which consist almost entirely of ions of one mass only, i.e. practically pure isotopes; these ions are deposited on cooled metal surfaces, forming thin films of the desired isotope in a highly-enriched state. Two machines have been built at Harwell. The small one has been in operation since May, 1948, and with it stable isotopes of atomic weight up to 40 can be produced in milligram quantities. The larger machine started working in the summer of 1950 and has been used to separate the isotopes of uranium and several other elements.

The fourth method of isotope enrichment is known as the "chemical ex-

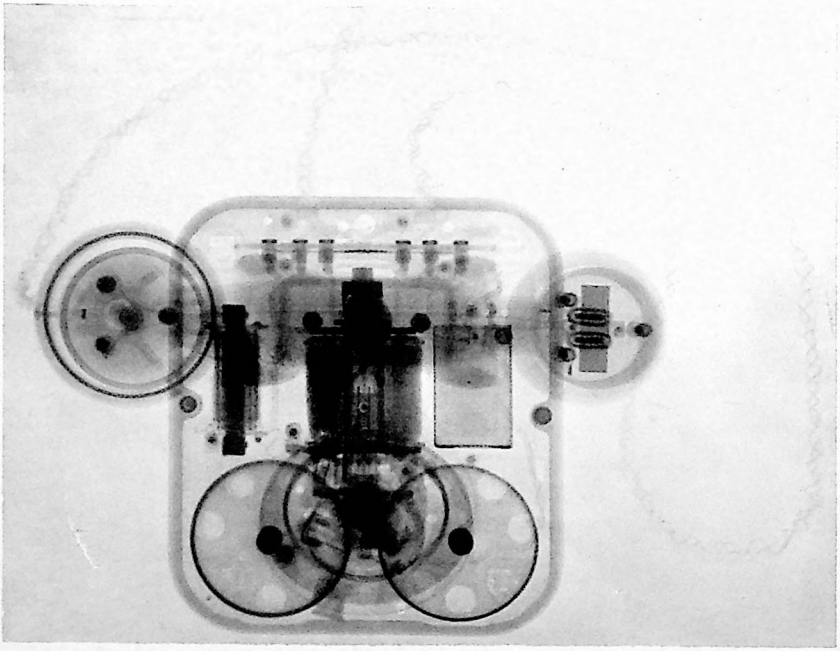


12. A static eliminator fitted on a loom to get rid of electric charges formed on the non-conducting fibres as the cloth is woven. Such charges may cause dust to stick deep in the fibres overnight and produce so-called fog marking in the fabric. The Shirley Institute at Manchester has developed a static eliminator consisting of a long bar-like source of thallium 204, suitably protected, which is hung over the warp at night. In the upper picture the weaver is lifting the source on to a tray before starting the loom in the morning.





13. A back-scattering gauge being used in the tin-plating works of Messrs. Richard Thomas & Baldwin at Ebbw Vale. The difference between the thickness of the plating and the desired thickness is indicated by the meter at the top left.



14. Radiograph of a telephone taken with the radioactive isotope gold 198.

change" method. It depends on very slight differences in chemical reaction rates between the isotopes of an element. The technique normally employed involves the countercurrent flow of two phases with exchange of an isotope-bearing group between the phases. Two examples are the separation of oxygen isotopes by exchange between carbon dioxide and water, and the concentration of nitrogen 15 by exchange between ammonia gas and a solution of an ammonium salt. The method gives relatively high enrichment and production rates, but becomes less and less feasible as the percentage difference in isotopic masses becomes smaller.

In connexion with the stable isotope work at Harwell, several mass spectrometers are available for mass analysis, and in certain circumstances analyses can be made for workers outside the Establishment.

The Isotope Information Office

The primary duty of the Isotope Division at Harwell and the Radiochemical Centre at Amersham is to produce isotopes, radioactive and stable, for use in British research and industry, and to help them to be used to the greatest advantage. In some fields, particularly medical and academic research, customers are acquainted with the possible applications of isotopes and with the experimental techniques necessary for their use. Industrial users, on the other hand, are ordinarily less well aware of the possibilities and are often complete strangers to the techniques. To such users, and to any who desire to avail themselves of it, the Isotope Division and the Radiochemical Centre offer an advisory service, manned by specialists, which will answer any enquiries on the use of isotopes and will give active help in performing experiments or setting up installations. Enquiries should be addressed to the Isotope Information Office, A.E.R.E., Harwell, Berks, or to the Radiochemical Centre, Amersham, Bucks.

Another aspect of this service to customers is the provision of training courses in the newly-opened Isotope School. An obstacle to the wider application of isotopes in research is the lack of workers familiar with the techniques of handling and using them. To overcome this, courses of four weeks' duration are now given at Harwell to students of graduate standing from hospitals, universities, other Government Departments, and industrial organizations. The courses (for which a charge is made) include lectures and laboratory work on the precautions necessary when working with radioactive materials, appropriate measuring instruments and technique, and the suitability of available radioisotopes for specific applications.

FIVE

THE REACTOR PROGRAMME

THE possibility that the large amounts of heat energy released in fission can be applied to the generation of useful power presents the outstanding challenge of our time to engineers and technologists, and if this possibility is translated into practice the world's effective fuel reserves may be greatly increased. This will be of special importance in countries where other sources of power are severely limited, as in Great Britain where we have no oil, relatively little water power, reserves of coal for only 200-300 years, and a rapidly-increasing demand for fuel with little prospect of substantially increasing supplies. There are also specialized cases where the small weight of nuclear fuel is of importance; thus a ship driven by a nuclear power plant could cruise for several years without refuelling. It is unlikely that the industrial use of nuclear power would lead to cheaper electricity than when orthodox fuels are used, since the costs of distribution of electricity represent a substantial fraction of the total costs, and capital costs of nuclear power stations will be larger than those of conventional power stations. The economic and social aspects of these possibilities have been discussed in a number of places, some of which are listed in an appendix to this account. We shall not consider them further but turn to the work which Harwell has done on the subject.

During the four years since its foundation the Establishment has considered many of the possible lines of attack on nuclear power generation. As a result of these studies the problems to be solved have been formulated and the necessary experimental investigations are proceeding. The only method for producing power which is likely to succeed in the next decade is the use of a reactor as a furnace, transferring the heat to a conventional electrical generating plant. The first questions to be settled therefore relate to the choice and construction of the best type of reactor for the purpose, and the development programme that has been drawn up is essentially a reactor programme. It falls into two parts. The first is a theoretical examination of the problem to decide which sorts of reactor are most likely to be successful; the second a two-stage experimental programme to determine accurately the data required for practical design and to test prototype reactors. The main part of the preliminary theoretical programme has been completed and the first stage of the experimental programme is well under way. On the basis of the theoretical work, design studies are proceeding at Harwell and in industry on reactors for the development of power production and for the study of breeding. A prime requirement is that the reactor shall develop heat at a temperature high enough to enable it to be converted into power efficiently, and in the first case it is necessary to design for economical use of the nuclear fuel. Since the capital cost of reactors is high, the reactors should have long lives to keep depreciation charges to a reasonable level. The overall operating

costs must be kept down as far as possible and the principal components of this are the costs of providing and processing the nuclear fuel. In the following paragraphs we shall first review the possible classes of reactors and then consider the particular designs which have been chosen for detailed study.

Possible classes of reactors

There are three general classes of reactors to be considered, viz., slow, intermediate, and fast, where these adjectives refer to the relative speeds of the neutrons causing fission. Gleep and Bepo are examples of a slow-fission reactor; the neutrons are slowed to thermal energies by means of a moderator. The nuclear fuel may be natural uranium, uranium enriched in uranium 235 (i.e. containing several times the natural proportion of 0.7 per cent uranium 235), or one of the two artificial fuels, plutonium 239 or uranium 233. A natural-uranium, graphite-moderated reactor is a big thing (cf. Bepo); if heavy water were used as moderator the volume of the core could be reduced from five to ten times, and if enriched uranium were used as fuel a still greater reduction would be possible. No reactor of this kind has yet been built that will run at the desired high temperatures.

The next class of reactors, called intermediate reactors, lies between slow- and fast-fission reactors in both design and function, since most of the fissions are produced by neutrons slowed down to energies intermediate between the high energies of fission neutrons and the low energies of thermal neutrons; this energy range is also called the resonance range, because the fission cross-sections of the fuel atoms relative to other cross-sections may be usefully higher than in the thermal region owing to resonance effects in the nucleus. Intermediate reactors employ some moderator, which need not be a very light material like carbon, and can be smaller physically than corresponding slow reactors.

The third class is the fast-fission reactor. In this, fission is produced by neutrons whilst they are still moving with the high speeds with which they are born. No moderator is needed. The fuel may be uranium greatly enriched in uranium 235, or plutonium 239 or uranium 233. The heat generated in fission would be removed and transferred to the power system by a coolant flowing past the metal-sheathed fuel elements.

Within each class of reactor, there are several possible variants in the design. For example, a slow-neutron reactor may use natural uranium or enriched uranium as a fuel, graphite or heavy water or perhaps beryllia as a moderator, air or helium or water or a liquid metal as a coolant. And after choosing a particular reactor, all the main dimensions must be chosen to give the best compromise for the particular purpose for which the reactor is required, so that a very great number of designs are possible, and the choice of the best ones for detailed study or for construction is difficult.

Breeding

Before going on to the Harwell programme, another important possibility in design should be mentioned, and that is breeding. This is of some interest, since

it offers the unique possibility of a furnace which, in developing energy by burning a primary fuel, will produce in the process a greater amount of an equally efficient secondary fuel than it consumes of the primary fuel.

Breeding, like the chain reaction, depends upon the fact that when a single neutron causes the fission of (say) a plutonium atom, more than two new neutrons are born. The mechanism is as follows for a reactor using as fuel a mixture of plutonium and uranium 238. A single primary neutron strikes a nucleus of plutonium and produces, let us say, $(1 + x + g)$ secondary neutrons. Of these secondaries, one goes to carry on the chain reaction, x (say) are lost by capture in materials or by escape, and g are captured by uranium 238 nuclei to form plutonium. So for every atom of primary fuel burnt, g atoms of secondary fuel are produced. If g is greater than one, more atoms of plutonium are produced than are consumed. This is called breeding and g is called the gain factor of the reaction.

A second breeding reaction, which may also be of long-term importance, is the production of a secondary fuel, uranium 233, from thorium 232. This takes place when thorium 232 captures a slow neutron, according to the scheme

$$Th^{232} + n^{1} \longrightarrow Th^{233}$$
$$Th^{233} \longrightarrow Pa^{233} + \beta$$
$$Pa^{233} \longrightarrow U^{233} + \beta$$

An advantage of this reaction is that it is easier to separate uranium 233 from thorium than plutonium from uranium, and that uranium 233 is somewhat less dangerous to health than plutonium. There are also very substantial supplies of thorium in the world in fairly concentrated form.

Breeding is important because the primary nuclear fuel uranium 235 is scarce. Breeding may allow the secondary fuels plutonium 239 and uranium 233 to be produced from the more abundant uranium 238 and thorium 232, thus increasing greatly the potential reserves of nuclear fuel.

An idealized breeder pile would consist of a central reacting core surrounded by a thick skin or shield of the isotope in which breeding was to take place. Thus the reacting core might be plutonium whilst the skin was uranium 238, or the system might consist of a uranium 233 core surrounded by a thorium 232 skin. Ideally nothing but fission reactions would take place in the core and transmutation reactions in the skin; if this ideal could be achieved there would be no fission products in the skin and the separation of the fuel atoms created from the parent isotope would be simple. Such an ideal is of course impossible of attainment, but the proportion of fission products in the skin of an arrangement of this kind is likely to be considerably lower than that in the slugs of a reacting core, such for example as the plutonium-producing reactors discussed in Chapter 3.

The Harwell programme

As has already been said, Harwell's first task in the reactor field was a theoretical study of possible types of reactor. This has been completed and as a result design and feasibility studies are proceeding on the following reactors:

(1) A slow-neutron, enriched-uranium reactor designed as a prototype power unit for special applications such as ship propulsion.
(2) A slow-neutron, natural-uranium reactor designed to develop power for electricity production.
(3) A fast or intermediate reactor designed to develop power and conserve fissile material by means of the breeding principle.

In parallel with these studies, laboratory investigations are in progress, both at Harwell and in industry, to solve the physical, chemical, and metallurgical problems involved. In the following sections we shall first consider in more detail the three reactors mentioned above, and then go on to mention some of the main technological problems that are being studied.

Slow-fission enriched reactors

The first major development in Harwell's reactor programme is the design of a pile rather similar to Bepo, but working at a much higher temperature—perhaps up to 600° C. The heat will be transferred to a steam boiler and the steam raised will be used to generate power in a conventional way. One of the unfortunate features of reactors using natural uranium as a fuel is that they cannot be built on a small scale. The theoretical minimum critical size is quite large, and in practice is increased considerably by engineering requirements such as canning the uranium, provision of heat transfer fluids, and the high operating temperature. Large size means high expenditure, and to build a small pilot plant, enriched uranium (i.e. uranium with the 235 isotope content increased) must be used. It is this type of reactor which is now being studied. A great deal of development work is required, and some of the technological problems, such as the use of beryllium or zirconium for canning, are mentioned in a later section of this chapter. A troublesome development period is invariably required in introducing new materials into industrial use, and metallurgical difficulties must be expected in operating the experimental reactor; but it is to solve such problems that pilot plants are built before proceeding to full scale.

Although it is not possible to go into technological details, some purely illustrative figures for such a reactor may be of interest. The weight of the unit will be determined primarily by the weight of the radiation shield, and for an output power of 10,000 kilowatts this will be several hundred tons. If the charge of fuel were to contain 100 kilograms of uranium 235, it would require 3½ metric tons of uranium metal with the natural uranium 235 content enriched fourfold. If the efficiency of power generation were 25 per cent, the reactor would have to develop 40 megawatts of heat to provide an output of 10,000 kilowatts of electricity, and would therefore require to burn about 40 grams of uranium 235 a day. In a year's full operation, therefore, 15 per cent of the fissile material would be consumed. By this time a good deal of reactivity would be lost, and it might be necessary to refuel.

Design studies of a reactor of this type are being carried out in collaboration with industry, and feasibility studies and cost estimates are expected to be completed early in 1952. It is hoped that it will then be possible to go ahead with building the first experimental reactor.

This type of pilot plant could lead to two possible developments in nuclear power. It could be the prototype of a power unit which could be used for special forms of marine propulsion, where the expense of the enriched fuel might be justified. Alternatively, the experience gained could lead the way to larger reactors using natural uranium as a fuel.

Natural-uranium reactors

A natural-uranium reactor of the type just mentioned might be built with a power output comparable with that of the standard coal-burning units used by the British Electricity Authority. However, an important limitation of this type of power unit is that its utilization of uranium is very poor. At the best it would use only 1 per cent of the uranium—made up of most of the uranium 235 content and some uranium 238 after conversion into plutonium—and at the worst only one-third of this. On this basis, to supply the present annual electricity consumption in the United Kingdom of 38,000 million kilowatt hours, about 600 metric tons of uranium would be required annually. Any extensive power development by such units would therefore require large supplies of uranium, and these could only be supplied from low-grade deposits. The cost of uranium fuel will depend largely on the cost of extraction from these low-grade ores. Although this problem is being studied intensively, it will be some time before there is enough information to judge the economics of such a power system.

Fast and intermediate reactors

The inefficient utilization of uranium in the natural uranium reactor that has just been described is a fundamental disadvantage. It is therefore desirable as a longer term policy to study other types of reactor which would use uranium more efficiently, by using the breeding principle mentioned earlier. In a breeding reactor it is necessary to avoid the wasteful absorption of neutrons in the thermal region. It must therefore be designed so that the neutrons produced in fission cause further fissions before they are slowed down to the thermal energy region. This can be achieved in a reactor of either the fast-fission or the intermediate class. Both classes require the use as fuel of plutonium or of uranium highly enriched in uranium 235.

The core of such a reactor would be quite small—one or two feet in diameter—and the neutron flux would be very high. The small size complicates the problem of removing the heat generated, since there would be a compact mass at a high temperature and with a comparatively small area of surface from which to collect the heat. It is probable that a reactor of this type would consist of fissile material enclosed in tubes past which liquid metal coolant would flow in a closed circuit; the outer part of the coolant circuit would be in the boiler or heat exchanger.

There are, however, many other possibilities: for example, the fuel and the coolant might be mixed together (such a design is called a homogeneous re-

actor); or the fuel elements might be used in some other arrangement than rods, so as to increase the surface area available for heat transfer from the fuel. The choice of a design for an experimental reactor of this type is thus much wider at present than that for the slow-fission reactors previously described.

Technological problems of power production

The reactor programme that has just been outlined demands the solution of many technological problems, and a considerable programme of research on these is now under way at Harwell, involving practically all the Divisions of the Establishment.

The outstanding problem is the metallurgical one of finding materials which will withstand high temperatures of operation whilst being at the same time bombarded by dense streams of neutrons and other radiations. The temperatures will be several hundred degrees centigrade higher than any so far used in nuclear reactors: thus for a steam-generating plant a fuel element temperature of at least 500° C. is desirable whilst for a gas turbine the temperature should be at least 750° C. In these circumstances it is no longer possible to enclose the fuel elements in aluminium, as is done in Bepo, but some other coating material must be found which must have a high melting-point, low neutron absorption, and high heat conductivity. Several different methods of tackling this problem are being investigated in the Metallurgy Division. The first method is to can the uranium in the conventional way but with a metal better able to withstand high temperatures than aluminium. Two possible metals are beryllium and zirconium. Neither of these has been much used in the past and consequently methods of extracting them with the requisite purity, and of fabricating them, have to be worked out. Already beryllium has been fabricated into rods and tubes. Advances have been made in the metallurgy of zirconium. One drawback to the latter metal is that it is usually contaminated with hafnium, which absorbs slow neutrons strongly. Harwell chemists and chemical engineers have, however, developed laboratory methods of separating the two metals to the small pilot plant scale, in order to produce quantities of hafnium-free zirconium for metallurgical work. The development is being continued to obtain data for production scale plant.

A second method of covering fuel elements which is being investigated consists in coating the uranium with a layer of the canning metal, instead of putting it in a container. This method would have the advantage that the thermal contact between the slug and its skin would be as perfect as possible, which would be a great help towards obtaining the very high heat transfer rate needed, particularly in a fast reactor. Various possible metals, and various methods of coating uranium with them, are being investigated.

The suitability of various possible canning or coating materials depends not only upon their thermal and mechanical properties at high temperatures but also upon the effect on the materials, and on the fuel elements themselves, of the intense neutron bombardment to which they would be subjected, especially in a fast reactor. This problem of the effects of bombardment by intense fluxes of

neutrons and of other radiations is one that crops up in all aspects of development, in connexion with all the materials used, particularly the moderators in thermal reactors. The investigation of them has thrown up a number of fundamental problems the solution of which will add to our knowledge of the properties of aggregates of atoms, particularly in the form of regular lattices as in crystals.

In addition to ensuring that sheathing materials have the right nuclear and thermal properties, it is also necessary to examine them from the point of view of possible reactions, produced or stimulated by irradiation, with the fuel elements. Both fuel elements and cans must remain stable under intense radiation at high temperatures.

Then there is the problem of removing heat from the fuel elements. We have seen that graphite-moderated slow-fission reactors working at moderate temperatures can readily be cooled by air currents (as in Bepo) or by water (as in the American piles at Hanford). If gas is used at high pressure and in a closed circuit, the method of gas-cooling can also be used for slow-fission reactors working at quite considerable temperatures. In one set of experiments on gas-cooling which was done at Harwell the heat transfer and flow characteristics of air passing over a pile of balls were measured; this was in connexion with a proposal to use spherical fuel elements. It is even possible that gas-cooling could also be used for intermediate piles working at higher temperatures, but the problem of removing the heat becomes progressively more difficult as the temperature of operation increases and the size of the critical mass of fissile material diminishes. This is, of course, because the area which the hot fissile material presents to the coolant is small, so that a great deal of heat must pass in a short time between the two. The coolant must therefore be a ready conductor of heat and have a high heat capacity. To meet these requirements for fast reactors it has been suggested that liquid metals (e.g. molten sodium, or a molten alloy of sodium and potassium) should be used in a closed circuit. That is, the coolant would be pumped round tubes from the reacting mass to a heat exchanger and back into the reacting mass continuously. A difficulty that arises in connexion with these particular metals is the ease with which they are oxidized. Experiments are now going forward to find the best method of circulating them in a closed system with the least amount of oxidation, and a pilot scale system has operated successfully for several hundred hours. Another liquid metal that might be used is mercury and its heat transfer properties are being studied.

Molten metals have the advantage, apart from their desirable thermal properties, that they can be pumped round a circuit by means of electromagnetic induction pumps which have no moving parts. The value of such an arrangement is clear when one considers the high temperature of the cooling liquid and the highly radioactive state which it soon attains, for it is a disadvantage of metal coolants that they become exceedingly radioactive as a result of bombardment by neutrons. There are, of course, other difficulties to be overcome as well. There is the possibility of chemical reactions between the metal coolant and the canning material surrounding the fuel elements, and of the erosion of the cans by the fast-flowing cooling fluid. Moreover it has to be remembered that these

processes, as with any others in a reactor, must be studied at high temperatures and under intense irradiation. All these problems are being actively investigated at Harwell.

The examination of the nuclear properties of possible reactor materials also is a matter of urgency, for the design of reactors cannot proceed far without these data. These properties are the fission, absorption, and scattering cross-sections, of the nuclear fuels and moderators and coolants, for neutrons of all the energies concerned. The range of energies involved is enormous, running as it does from one-fortieth of an electron volt at thermal energies to two million electron volts at fission energies; that is a range of about four hundred million to one. It is obvious that no single technique for making these measurements could be used throughout the range. In fact at least three quite different methods are used. A more detailed account of these methods will be given in other chapters. Here, it may be remarked that at thermal energies a neutron velocity selector and a neutron crystal spectrometer are used; at intermediate energies, neutron pulses are produced by means of a linear accelerator; whilst at fission energies a Van de Graaff electrostatic generator is used. Many absorption measurements at thermal energies are also being made by means of Gleep and Bepo.

It will be seen that a large proportion of the preliminary research for reactors falls upon the metallurgists and physicists. This is not to say that there are no problems for the chemists. On the contrary, they are already engaged upon an extensive programme of research into such matters as the chemistry of fuel elements, the chemical effects of radiation upon constructional materials, and the chemistry of materials like beryllium and zirconium. But a field of enquiry which is pre-eminently that of the chemists and chemical engineers arises from the need for separating secondary fuel elements, plutonium and uranium 233, from the breeding materials uranium 238 and thorium. The ideal would, of course, be a continuous process in which the secondary fuel was extracted from the breeder material more or less as it was formed; it is possible that this may one day be achieved, but at present it is no more than a chemical engineer's dream.

There is another important and difficult problem of which the economic consequences cannot be accurately foretold at present, and that is the disposal of the vast quantities of radioactive waste products, mainly fission products, which would accumulate in the course of processing nuclear fuel elements. As an indication of the order of magnitude of the quantities involved, it may be said that if the whole of the world's power supply was obtained from nuclear sources, the radioactivity of the accumulated waste products at the end of a year would amount to 1,000,000,000 (10^9) curies, i.e. would be equivalent to 10^9 grammes (1,000 tons) of radium. If this amount could be distributed uniformly throughout the enormous volume of the Atlantic Ocean, it would raise the radioactivity of that ocean by a significant, though not dangerous, amount. In fact, however, it would be impossible to distribute the waste uniformly, and if waste were discharged into the ocean high concentrations would build up which could not be tolerated; experiments have shown that dispersal from any point is slow and it is unlikely that more than 3,000 to 30,000 curies a year could be dispersed from any one point of discharge. Fortunately the physical bulk of this enormous

amount of radioactivity can be made fairly small—if a year-old bulk of fission products of activity 10^9 curies were evaporated to dryness, it would occupy a volume of only one cubic metre—and therefore there is a possibility of storing the products in tanks surrounded by thick shields of concrete until their radioactivity has in the ordinary process of nature decayed to a reasonably low level. The half-life of most fission products is comparatively short and consequently the time taken for the greater part of the activity to decay would not be intolerably long, but the residual activity from long-lived activities would still be a serious problem. Provision would have to be made for the dissipation of the heat developed, for decomposition of any liquid solvent, and for measures to provide against failure of the storage vessel by corrosion or otherwise. These are problems which are being considered at Harwell and also by the production organization at Risley.

It will be clear from what has been said in this chapter that there are very many questions which must be answered before power derived from nuclear sources can become available economically. It is probable that the next three to five years will see the completion of the first experimental reactors. There will then follow a period, probably also five years, during which experience in the operation and development of these reactors, and of the heat-exchanging and power-generating equipment associated with them, will be gained. At the same time the questions of processing nuclear fuel and developing and improving constructional materials will be under examination by the chemical engineers, chemists and metallurgists. Clearly no very certain estimates can be made of the time-scale of this work, but it is the opinion of those best qualified to judge that a decade will elapse before we shall be able to say whether economic generation of power by nuclear fuel is possible.

SIX

THE ACCELERATOR PROGRAMME

IN any laboratory devoted to the study of the atomic nucleus a conspicuous place is taken by machines for accelerating elementary particles to high energies. Most people are familiar with the idea that these atom-smashing machines, as they are not very accurately called, are necessary to modern nuclear research, and most people are accustomed to newspaper announcements of the development of new and yet more powerful machines. There is, however, not such a wide understanding of the purpose of these machines or of the reasons for the existence of many different kinds and for the continual striving for higher and higher energies. We shall preface this chapter, therefore, with a brief account of the applications of the different machines. This will be followed by a short description of the various types at Harwell, more detailed accounts of which will be given in subsequent publications.

The purpose of particle accelerators

Everyone knows that the atom is so very small that there is no possibility that either it or its even smaller nucleus can ever be seen or examined by ordinary means. Yet physicists have clear notions about the size and composition of the nucleus as well as more exact ones about the arrangement of the outer system of planetary electrons, which has been studied for much longer than the nucleus. How has it been possible to do this? As far as the nucleus is concerned, although some information has been gained by studying the properties of radioactive atoms and some by examining the behaviour of ionized atoms in magnetic fields, the most fruitful method has been to bombard it with sub-atomic projectiles (in the form of the fundamental particles of matter) and to study the effect of the resultant collisions on both the nucleus and the projectile. From the changes in energy and momentum of the projectile, and from the appearance of new particles not present at the beginning of the experiment, a very great deal has been learned about the forces in and around the nucleus. For example in one of the classical experiments of physics, Rutherford, with Geiger and Marsden, first demonstrated that the atom had a massive charged nucleus by firing swift α particles at atoms of gold and measuring the angles through which they were deflected. The experimenters found that some of the particles were turned through very large angles and they showed that this fact could be explained only on the assumption that at the centre of the atom there was a positively-charged nucleus containing virtually all the mass of the atom. Upon the basis of this hypothesis the whole structure of modern nuclear theory has been erected.

In these experiments the projectiles were the α particles released in the natural radioactive decay of radium. Their energy was not great and consequently

they were repelled by the strong positive charge of the gold nucleus before they could get close to it. There was certainly no possibility that they could penetrate the nucleus, although, as Rutherford showed later, they were energetic enough to penetrate the light nucleus of the element nitrogen and to knock out one of its constituent protons. It was clear that if the details of the structure of the nucleus and the exact nature of the electric fields surrounding it were to be elucidated, very much more energetic bombardment of both light and heavy nuclei would be necessary. Nuclear physicists accordingly began to consider ways by which elementary particles could be accelerated artificially to energies much higher than those of the particles available in nature. These considerations led to the development of particle accelerators of the kind to be described in this chapter.

Before the advent of accelerators only the three naturally-occurring particles were available, the heavy positively-charged α particle, the light negatively-charged β particle or electron, and the packets of electromagnetic waves known as γ photons; moreover the energies available were very restricted. By artificial means the power of the weapons in this armoury was enormously increased and there were added to it the positively-charged proton and deuteron and also the uncharged neutron. Neutrons are particularly valuable weapons because, being uncharged, they are not repelled by the electric field of the nucleus and consequently they can penetrate it far more readily than any charged particle.

Summarizing, particle accelerators are necessary to the nuclear physicist because one of his most powerful methods of studying the nucleus is to examine the interactions between it and the various elementary particles, moving with all energies from a thousandth of an electron volt up to, in the future, thousands of MeV. Different types of machine are used because not all particles can be accelerated by all machines and also because it is not economical to use the same machine for all energies. Other considerations that result in a multiplicity of machines include the requirement that for some experiments the energy of the particles must be known more accurately than for others and that some machines give a greater output of particles than others.

Single-impulse accelerators

All particle accelerators depend for their action on the fact that a charged particle is acted on by forces whenever it moves in either an electric or a magnetic field. Thus a particle in an electric field experiences an accelerating force directly proportional to the electric potential acting. On this principle is based the simplest kind of particle accelerator, the so-called constant potential type, which consists in essence of a long tube to the ends of which a high voltage is applied; the force exerted upon charged particles introduced at one end causes them to fly down the tube with ever-increasing speed until they strike the target at the other end. The first successful accelerator was of this type. It was designed by Cockcroft and Walton in 1932 and was used to produce the first disintegrations by artificially-accelerated particles. In this type of accelerator the high voltage is derived

from the alternating current mains by means of a transformer and an ingenious voltage-multiplying system using condensers charged by electronic valves acting as switches. The maximum voltage that can be produced is about a million, which is rather low by modern standards, but is still useful for certain types of experiment. The apparatus has the advantage of simplicity. An equipment of this kind, producing voltages up to 600 kV, is used at Harwell to study the reactions between deuterons and deuterons and between deuterons and tritons.

The Van de Graaff generator

A more powerful accelerator of the electrostatic type is that devised by Van de Graaff in America, in which an insulated conductor is made to attain a steady potential of several million volts by the accumulation of electric charge conveyed to it on a continuously-moving belt. The diagram (Fig. 2) illustrates the principle of the method. The charging comb S, which is connected to a 100,000-volt supply, sprays charge on the moving, insulating belt B. This belt, running on pulleys, carries the charge up the column to the inside of the high-voltage electrode E, which is supported on insulating pillars. Here the charge is removed by a collecting comb S to the electrode E. As E accumulates charge its potential rises until it reaches a steady value (set by the load and leakage currents) of several million volts. The whole machine is enclosed in a pressure vessel V. The steady potential generated is then applied to an accelerating tube in the same way as in the Cockcroft-Walton generator. The 4 or 5 million volts generated by a Van de Graaff machine may not seem spectacular compared with the rating of some other machines (though, as will be shown, a comparison in these terms is not quite fair), but the machine has the advantages that it can be made very stable in operation and the voltage is known with considerable precision. Consequently the energy of the beam of charged particles which it produces, though not very great, is steady and accurately known, and the spread of energy is small. These properties make the machine particularly suitable for exploring the energy levels of the nucleus, which demand precise measurements and are sometimes very closely spaced. It is important to note that even if the desirable characteristics of the Van de Graaff could be produced at much higher energies the range 3-10 MeV would still remain extremely important.

A large Van de Graaff machine, with a rated maximum voltage of 5 MV, has been designed and built at Harwell for research in nuclear physics. In this generator the high-voltage electrode is a cylinder topped by a hemisphere, the whole being supported by three columns of insulators; these insulators are

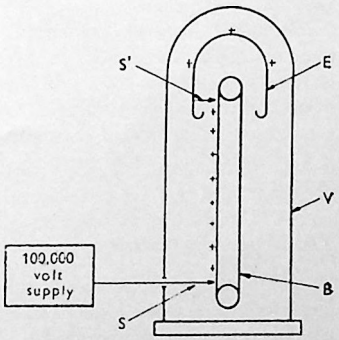


Fig. 2. Schematic diagram of Van de Graaff machine.

separated by circular aluminium plates which help to equalize the potential distribution. The charging belt runs in the vertical space between the insulating columns. The generator and accelerating tube, which are some nine feet high, are enclosed in a welded steel pressure vessel filled with a mixture of nitrogen and freon to a pressure of several hundred pounds per square inch. The machine was built very largely in the Engineering Unit at the Telecommunications Research Establishment, Malvern, though some of the parts were made by other Ministry of Supply establishments and by industrial contractors. The construction and testing of the generator occupied two years; the development of a satisfactory accelerator tube has been particularly difficult and has not yet been completed, but nuclear physics experiments have begun using rather lower voltages than the maximum of which the generator is capable. Further development of this type of generator is not being undertaken, but a study has begun of the fundamentals of dielectric breakdown at high potential, from which it is hoped to develop better accelerating tubes. A smaller Van de Graaff generator, with a maximum rated voltage of 2 MV, has been built by an industrial contractor and installed at Harwell for the Chemistry Division. Some of the work for which this is used is described in Chapter 8 (p. 79).

Cyclic accelerators

In the electrostatic generators just described the particles are accelerated along a straight path by a single application of the high voltage, i.e. by a single electric impulse. Another class of accelerators is that in which particles are accelerated in a spiral or circular path. The accelerating field may be applied continuously or in a large number of successive impulses. Although these separate impulses are comparatively small, the total energy imparted to the particle can be made extremely large—hundreds or even, it is hoped, thousands of millions of electron volts. The particles are constrained to move in circular or spiral paths by means of magnetic fields, and are accelerated in these paths by electric fields. The machines will generate particles of extremely high energies but they are not precision instruments in the sense that the Van de Graaff generator is, so that the mean energy of the particles in the beam is seldom known to better than a few per cent. In addition there is a much greater spread in the energy, so that the beam of particles is not homogenous but contains particles of all energies over a range on either side of the mean energy. For most purposes, however, this is a comparatively small price to pay for the very large energies that can be produced.

The 110*-inch cyclotron*

The biggest machine in this category at Harwell is the synchro-cyclotron, the largest so far operating in Europe. In this machine a strong magnetic field is produced between the horizontal circular poles of a very large electromagnet. Between these poles is placed an evacuated chamber containing a hollow copper electrode called, from its shape, a dee; enveloping the dee (except along its

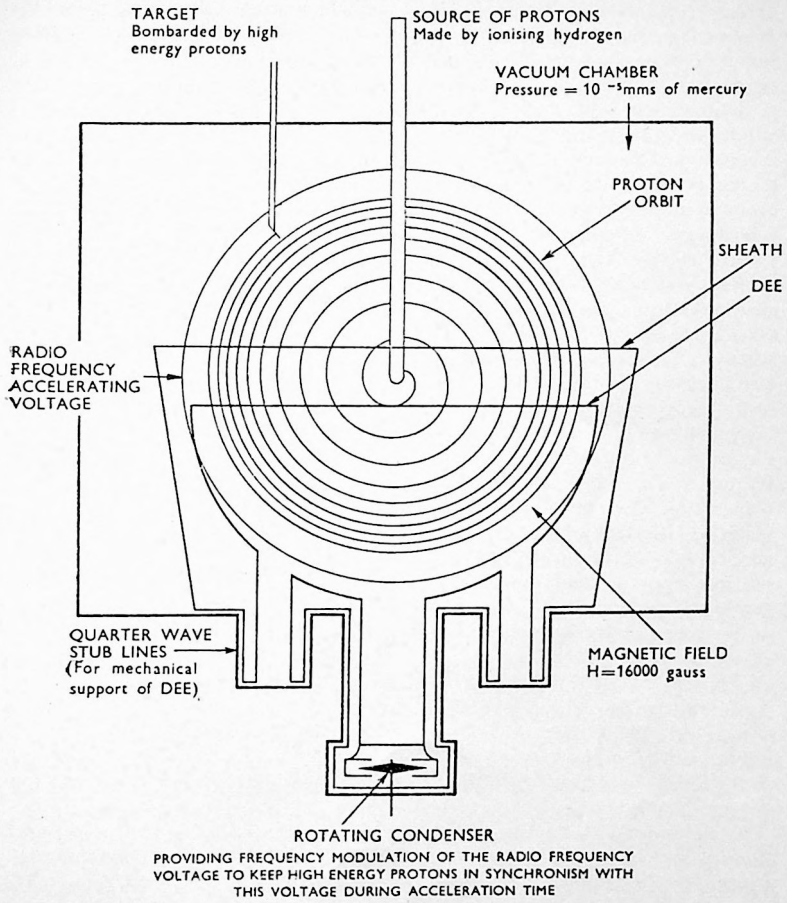

TARGET
Bombarded by high energy protons
SOURCE OF PROTONS
Made by ionising hydrogen
VACUUM CHAMBER
Pressure = 10 $^{-5}$mms of mercury
PROTON ORBIT
SHEATH
DEE
RADIO FREQUENCY ACCELERATING VOLTAGE
QUARTER WAVE STUB LINES (For mechanical support of DEE)
MAGNETIC FIELD H=16000 gauss
ROTATING CONDENSER
PROVIDING FREQUENCY MODULATION OF THE RADIO FREQUENCY VOLTAGE TO KEEP HIGH ENERGY PROTONS IN SYNCHRONISM WITH THIS VOLTAGE DURING ACCELERATION TIME

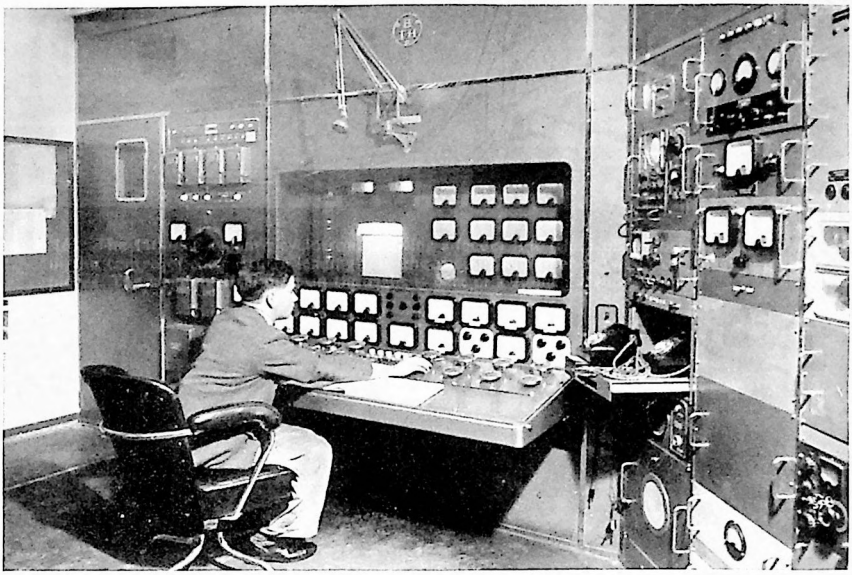
Fig. 3. Principle of the synchro-cyclotron.

diameter) is another copper electrode called the sheath, which is earthed. The principles on which the machine operates can be understood from Fig. 3. In this diagram (which is in effect a horizontal section through the machine) the area of the magnetic field is enclosed by the circle, with its lines of force running perpendicular to the plane of the paper; the dee is shown in outline, surrounded by its sheath, also in outline. The area between the straight edges

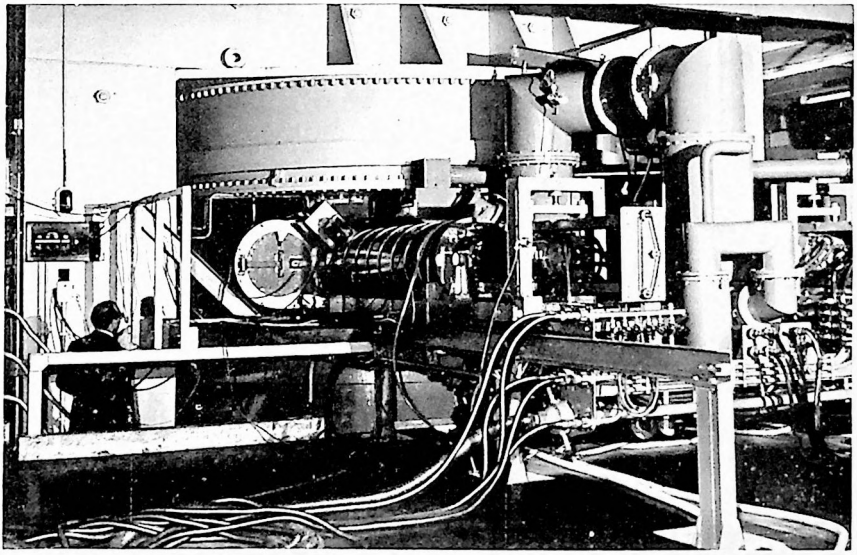
of these electrodes represents the region in which acceleration takes place; the accelerating field in this region is produced by an alternating electric potential set up between the edges of the electrodes by radiofrequency energy, which is fed to them. Suppose now a proton (or other heavy charged particle) is moving in the magnetic field. As long as it remains outside the accelerating region it will move with its original velocity in a circular path, into which it is forced by the action of the magnetic field. As soon as it moves into the accelerating region, however, it is accelerated by the action of the electric field. It therefore acquires more energy and, on emerging again into the non-accelerating area, continues in a circular path, but the circle now has a larger radius. On completing another half-circle it again enters the accelerating region and, if the frequency of alternation of the electric field is properly chosen, it again receives an accelerating impulse and emerges with still more energy and on a circle of still larger radius. The path of the particle thus becomes an expanding spiral, as shown in the diagram. At the same time its energy is increased with every crossing of the accelerating region. Now it is a fact (explicable by relativity theory) that as the speed of a particle approaches that of light, its mass increases. One consequence of this relativistic mass increase is that it takes longer for the particle to complete one revolution of its orbit; if, therefore, the frequency of the alternating accelerating field remained unchanged, there would come a time when the particle would get out of step with the field and so would reach the accelerating area when the voltage was in the wrong direction to accelerate it. This difficulty is overcome in the synchro-cyclotron by decreasing the frequency of the alternating voltage as the particle moves out from the centre to the periphery of its path, so that the accelerating impulses are applied at increasing intervals of time corresponding to the increased time of revolution in the orbit(1). In the Harwell cyclotron the frequency is decreased from 26 Mc/s to 20 Mc/s as the proton moves along its spiral path from centre to outside edge. The proton takes only a few thousandths of a second to traverse something like 300 miles, and in doing so its speed increases from nearly zero to about half that of light, i.e. nearly 100,000 miles a second. The proton is started on its long journey by a proton source, from which it emerges with a very low energy.

The synchro-cyclotron consists of a large direct-current electromagnet with circular pole-pieces between which is placed the vacuum tank containing the dee and its sheath; the accelerating field is supplied to the dee by a large wireless transmitter. Very high energies might be achieved with these machines before any technical limitation is reached, but their cost, which lies mainly in the magnet, increases rather more rapidly than the energy. There is therefore an economic limit and it is unlikely that they will be used for energies greater than 400-500 MeV; for higher energies a proton-synchrotron would be more economical.

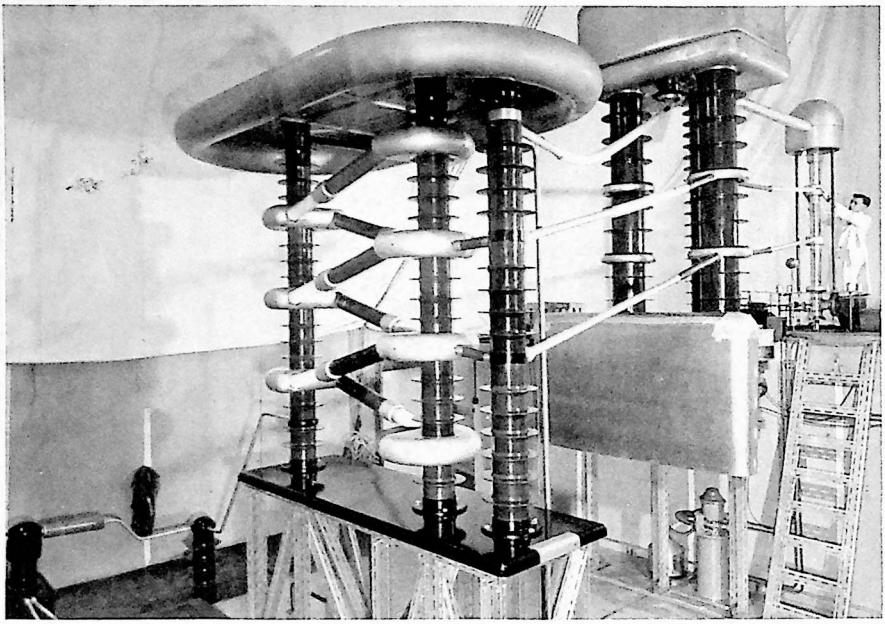
(1) The synchro-cyclotron, or frequency-modulated cyclotron, is a development of the conventional cyclotron, in which the frequency of the accelerating voltage is kept constant. Because, therefore, there is no way of compensating for the decrease in speed in its orbit of a particle in which the relativistic mass increase has become significant, the conventional cyclotron is not capable of producing particles with energies much over 50 MeV, whereas energies of several hundred MeV are possible with a synchro-cyclotron.



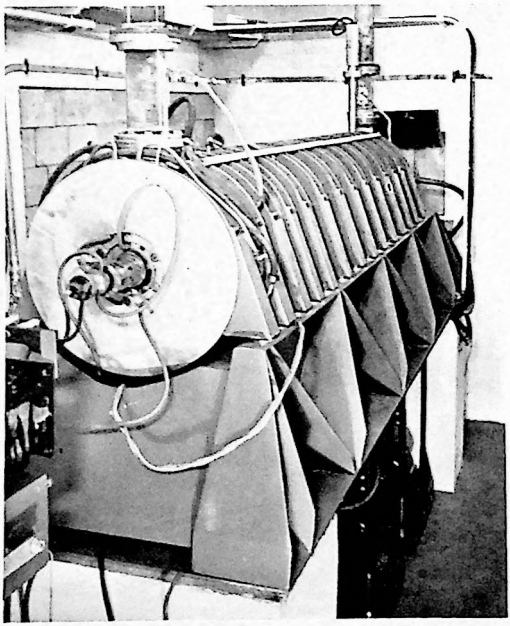
15. The control panel of the large electromagnetic separator used for the production of stable isotopes.



16. The 110-inch synchro-cyclotron, showing a feeder line (the ribbed horizontal cylinder in the centre of the picture) leading into the vacuum chamber between the magnet pole-pieces. The large vertical pipe on the right is part of a 20-inch vacuum pump.



17. The 600-kV high voltage set. The Cockcroft-Walton type generator is in the foreground, the accelerating tube at the back. The ion source is inside the dome at the top of the accelerating tube and the power supply for the ion source is mounted on top of the column between the generator and the accelerating tube. The latter projects through the floor of the platform into the room below, where the experiments are made.



18. The 4-MeV linear accelerator viewed from the gun end. The focusing coils are contained within the metal segments running the length of the machine; the corrugated waveguide which passes down the centre is concealed by these coils and the vacuum envelope.

In the Harwell machine the pole-pieces of the magnet are 9 ft. 2 in. (110 in.) in diameter. The complete magnet contains 670 tons of steel in 10-ton plates; it is excited by a coil wound of 70 tons of copper strip which consumes 355 kW of electrical energy at normal input. The resultant magnetic field has a strength of 16,000 gauss at the centre. To the sides of the magnet poles are sealed a stainless steel vacuum chamber some 14 ft. in diameter, in which a high vacuum (10^{-5} mm. of mercury) is maintained by three 20-inch diameter oil-diffusion pumps. Inside the vacuum chamber, and in the 12-inch gap between the magnet poles, is placed the large copper accelerating electrode, a semicircular box like a filled-in dee, surrounded by a second, earthed, electrode to concentrate the electric field. The dee is connected to a system of resonant coaxial transmission lines coupled to a single, 150-kW, water-cooled, triode valve to form a grounded grid oscillator. One of the dee transmission lines is terminated by a motor-driven variable condenser which varies the resonant frequency to produce the desired frequency modulation. Some idea of the scale of this equipment may be gained from the statement that the transmission lines, which are the same in principle as the screened cable used to couple television sets to their aerials, have an outside diameter of 20 inches, whilst the inner conductor consists of a copper tube shrunk on to a modified 5-inch gun-barrel.

Cyclotrons are suitable for accelerating heavy particles, protons, deuterons, α particles; they cannot be employed for accelerating electrons. In the Harwell machine, protons are produced by an ion source placed in the accelerating gap on the axis of the magnet poles and between the dee and its sheath. Protons of any energy up to the maximum may be allowed to strike a probe target which can be moved towards the centre of the system so as to intercept the spiralling beam of protons at any desired radius. The impact of the protons on the target results in the ejection of fast neutrons which are very penetrating. The machine has therefore to be elaborately shielded. It is installed underground, with six feet of concrete overhead, and is remotely controlled by a system incorporating safety interlocks and protective devices.

The Harwell cyclotron took about three years to design and build and many industrial firms took part in the work, particularly C. A. Parsons and Co. Ltd., who constructed the magnet. The more specialized parts were built by the Engineering Division at Harwell, and civil engineering and electrical works were done by Ministry of Works contractors. The machine went into operation at the beginning of December, 1949, and within a very short time it was producing protons with a kinetic energy of a little less than 180 MeV, corresponding to a velocity of about half that of light. The proton beam is generated in bursts or pulses with a periodicity corresponding to the frequency of the frequency-modulation cycle, which at present is 100 cycles a second. The duration of the pulses is usually about 100 microseconds. At present the mean beam current (a measure of the number of protons in the beam) is about 1 microampere, which is very satisfactory at this stage of the development.

At the full energy of 180 MeV it should be possible to produce mesons, the unstable particles (formerly called "heavy electrons") found in cosmic rays and thought to play an important role in holding the atomic nucleus together.

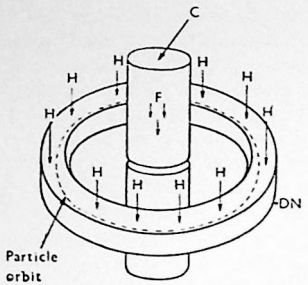


Fig. 4a. Principle of the betatron.

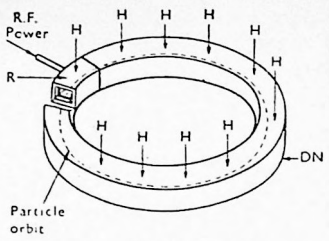


Fig. 4b. Principle of the synchrotron.

However, the yield of mesons at this energy is known to be small and it is not intended to spend a large proportion of operating time on meson experiments. More attention will be paid to the interactions between protons and neutrons and to the nuclear explosions produced by high-energy protons and neutrons. Neutrons being uncharged, they cannot of course be accelerated by a cyclotron or any other accelerator, but a beam of neutrons having energies up to that of the protons can be generated by allowing the protons to fall on a target inside the vacuum chamber; the neutrons escape from the vacuum chamber through a thin window with negligible loss on the way.

The electron synchrotron

Another cyclic accelerator is the synchrotron, in which the particles are made to travel in a circular path of constant radius (by means of a magnetic field) and are accelerated once in each circle by an electric field. In order to keep the particle moving on the same equilibrium radius, the strength of the guiding magnetic field has to be increased as the particles are accelerated. So far synchrotrons have been made to accelerate electrons only, although proton synchrotrons are being developed with which it is hoped to produce energies of several thousand MeV.

The synchrotron resembles another device for accelerating electrons, called the betatron, inasmuch as each uses a steadily-increasing magnetic field to keep the particles in an equilibrium orbit of approximately constant radius. The principle of the betatron is illustrated diagrammatically by Fig. 4a, in which DN represents an evacuated accelerating chamber shaped like a hollow ring, C represents a central magnetic core in which there is a changing magnetic flux F, H represents a guiding magnetic field acting peripherally. The electrons travel in a circular orbit in DN under the influence of the guiding magnetic field H (the magnet producing the field is not shown); they are accelerated in this orbit by the electric field induced by the changing flux F. There is a fundamental difference between this action and that of the synchrotron, the principle of which is illustrated by Fig. 4b. In this machine the accelerating

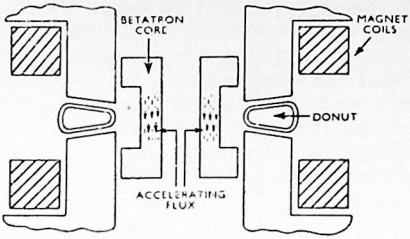


Fig. 5a. Vertical section through synchrotron.

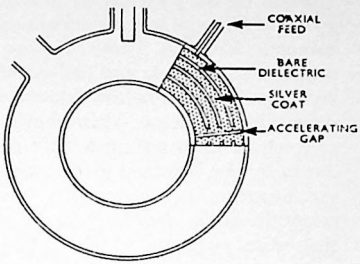


Fig. 5b. Horizontal section through synchrotron torus.

chamber DN is modified to include a short resonator R and there is no central magnetic flux. As in the betatron the electrons are guided in a circular orbit by the peripheral magnetic field H, but in the synchrotron they are accelerated by an alternating electric field set up in the resonator, the frequency of this field being synchronized with that of the electron in its orbit. Thus the electron receives an accelerating impulse every time it goes round. The synchrotron in fact uses synchronous electric accelerating impulses in a manner similar to that in the operation of a frequency-modulated cyclotron. Reverting to the betatron, the use of a changing magnetic flux to produce the accelerating field in a betatron requires a special iron core which adds greatly to the cost and size of the magnet and so of the complete machine. The betatron principle is, however, used in synchrotrons to provide the initial acceleration before the synchronous electric impulses are switched on; this is possible with only a small quantity of additional iron and considerably simplifies the synchronization of the electric impulses when they come into play. A diagrammatic sketch of the arrangement of the synchrotron is given in Fig. 5. The left-hand sketch is a vertical section through the machine, showing the magnet, magnet windings, betatron core, and a section through the accelerating torus. The right-hand sketch is a horizontal section through the torus, showing the arrangement of the resonator.

The synchrotron which we have described accelerates electrons only. The electrons so produced react with nuclei in a different way from fast positive or neutral particles. When they approach close to nuclei they experience strong accelerating forces due to the nuclear charges and lose their energy by radiating it as packets of electromagnetic waves, i.e. γ-ray photons of energy. These γ-rays, which have a wide range of energies, the highest being equal to the maximum energy of the electrons, may be used to eject neutrons, protons and α particles from nuclei by photodisintegration and even to split some of the heavy atoms into lighter fragments by photofission. High-energy electrons and the γ-rays which may be produced by them are also of great interest to members of the medical profession who wish to use these high-energy radiations both for therapy and biological research.

Work on the electron synchrotron was begun towards the end of 1945, by a group of Harwell scientists working at the Telecommunications Research Establishment, Malvern. These men had been engaged on microwave radar development during the war and had established themselves as leading exponents of the techniques needed to develop the new machines. Their first experiments were made with a betatron, which they modified; in August, 1946, they had it working as a synchrotron giving 8 MeV electrons, twice the energy that could be produced by the betatron in its original form. This was the world's first electron synchrotron. Its construction was an example of the international nature of scientific work—British radiofrequency technique had been combined with a theoretical suggestion made, independently, by an American and a Russian to produce an entirely new machine from one, the betatron, that had been proposed in principle years earlier by workers in America, Britain and Germany, and had been developed to practical form by an American.

Harwell's interest in the synchrotron principle was aroused by the possibility it offered of producing quite cheaply and quickly a machine capable of generating particles with energies in the region of hundreds of MeV. Work was begun on the design of a 30-MeV machine in order to obtain information for the design of very high energy machines, in particular a 300-MeV machine weighing 110 tons which is now being constructed by industrial firms in association with Harwell and the University of Glasgow, where it is to be used for nuclear research. It was also believed that a 30-MeV machine would be a useful research tool. The design work on this machine had begun before the opportunity arose of converting the 4-MeV betatron, but advantage was taken of this opportunity to test the synchrotron principle as early as possible, with the satisfactory results recorded above. At this time medical research workers had need of a high-energy x-ray source, for it was known that x-ray energies up to 30 MeV were likely to be useful for therapy. The Medical Research Council therefore asked that an industrial firm should make two 30-MeV synchrotrons to the same specification, and these have been delivered.

The new machine was first operated in October, 1947. Within a very short time it was producing γ-rays of energy nearly 30 MeV. After an initial testing period the γ-ray output intensity was increased to 10 roentgens/minute at a distance of 1 metre from the target; this figure was later increased to 17. The electrons travel around a circular orbit 8 inches in diameter, in a highly-evacuated glass chamber shaped like an American doughnut, that is flat with a hole in the centre; indeed, following American spelling, these chambers are commonly called donuts. In one segment of this chamber is placed a resonant cavity which is excited by a small wireless transmitter working on the very short wavelength of about 63 cm. It is the alternating electromagnetic field set up in the resonator which provides the periodic accelerating force on the particles. In the course of accelerating to 30 MeV the electrons traverse their circular path no fewer than two million times and cover a total distance of a thousand miles, completing the entire journey in 1/200 of a second. The actual energy given to the electrons in each revolution is quite small; indeed nowhere in the apparatus is an accelerating voltage used greater than that of a normal wireless battery, yet the total

energy given to the electrons corresponds to an accelerating voltage of thirty million. The machine is now being used to study photodisintegrations by γ-rays and some interesting results have already been obtained.

The linear accelerator

The linear accelerator differs from the cyclic accelerators which have been described in that it accelerates the electrons in a straight line, but it is similar to them in that it does not require high voltages though the final energy of the electrons is many MeV. This is done by making the particles surf-ride, so to speak, on the crests of electromagnetic waves passing down an evacuated metal tube called a waveguide. The very short electromagnetic waves (wavelength about 10 cm.) are generated by a high-power magnetron valve of the kind developed for radar, and are fed into a length of corrugated waveguide, also descended from war-time radar developments. By designing the corrugations properly, the phase velocity of the waves is made to increase steadily as they advance down the tube, from a speed equal to that of the electrons entering to nearly that of light. This type of linear accelerator is called a travelling-wave linear accelerator.

Electrons can also be accelerated in a waveguide by waves which, owing to reflexions at the ends of the guide, form a stationary pattern. This so-called standing-wave or resonant guide principle was thought by many to be more promising than the travelling-wave method, but the Malvern Group believed in the latter and pressed on with their researches. Their faith was justified when, in November, 1946, they succeeded in operating a short length of guide, the first travelling-wave linear accelerator to operate anywhere in the world. This machine gave electrons of energy only about $\frac{1}{2}$ MeV but work began immediately on a larger machine which was operating at Malvern in 1948.

The new machine, which has recently been rebuilt and installed at Harwell, is 2 metres long and produces strong beams of electrons with energies between 3.5 and 4 MeV, with a mean beam current of 100 microamperes. The general arrangement is shown schematically in Fig. 6. The electrons travel down the axis of the waveguide, and emerge from a thin metal window placed at the end. The compactness of the machine, the high beam currents accelerated, and the ease with which the beam is extracted are all attractive features. These qualities make it very suitable for medical purposes, and the Harwell team has collaborated closely with the Medical Research Council and an industrial firm in the design of a 10-MeV machine for medical use. The first tests of this machine have been made with satisfactory results.

In the Harwell machine the magnetron valve, which generates the accelerating waves, is switched on for brief pulses of two-millionths of a second duration, 200 times a second. The electrons are consequently accelerated in pulses, and the current in a pulse is very great, as much as 100 milliamperes; when this is used to produce x-rays an intensity of as much as 130 roentgens/minute at 1 metre can be obtained. For nuclear physics use, a pulsed x-ray beam produced in this manner can be made to yield a pulsed neutron beam of very great intensity, by

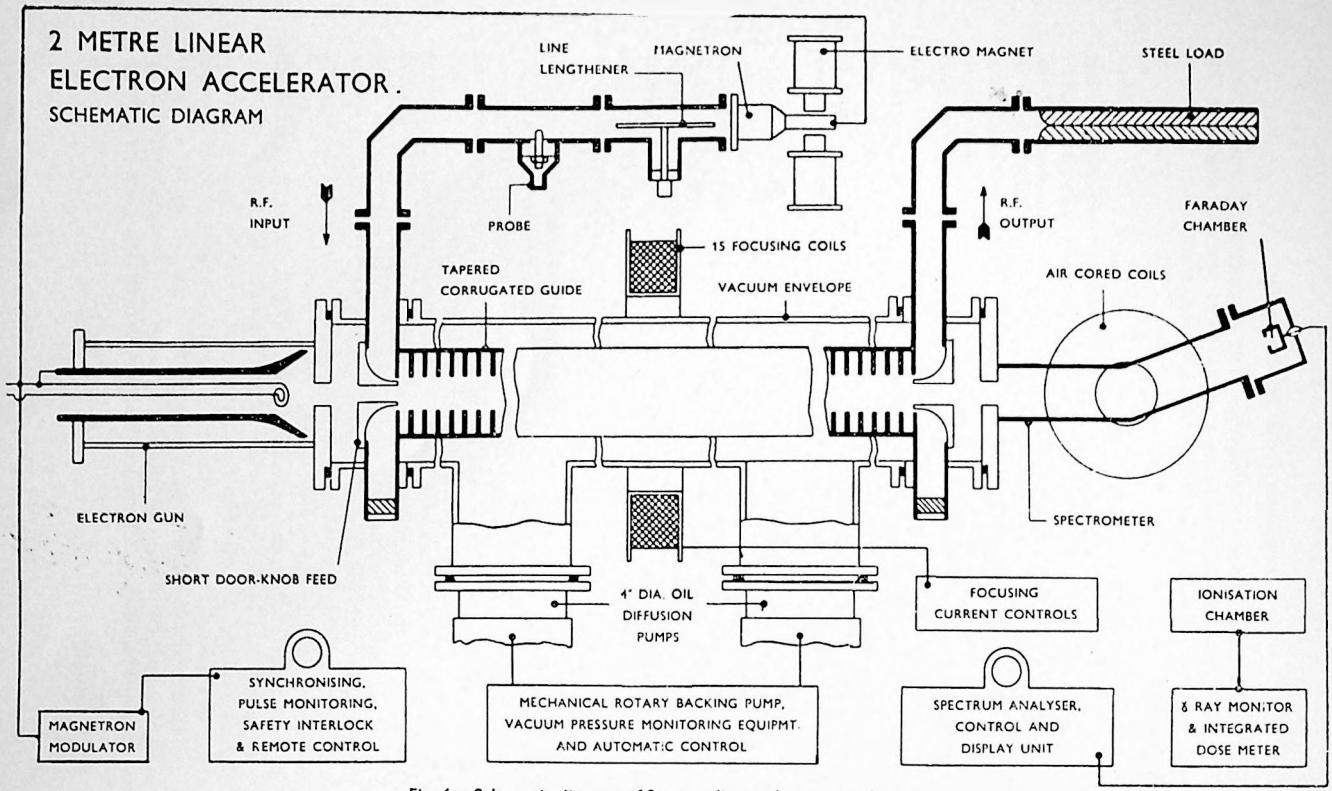


Fig. 6. Schematic diagram of 2-metre linear electron accelerator.

the photodisintegration of beryllium. The machine installed at Harwell is being so used and neutron beams with an average intensity of a thousand million (10^9) neutrons a second are obtained. The scientists who developed this machine are probably the most advanced in the world in their understanding of the principles, and knowledge of the practice, of electron linear accelerators. At present they are examining methods of improving the efficiency of travelling-wave linear accelerators by loading the waveguides with discs of ceramic materials having very high dielectric constants. If the promise of early calculations is fulfilled in trials now in progress it should be possible to build a machine producing electrons with an energy of 1,000 MeV; this would be about a hundred yards long.

With the exception of the work on electron synchrotrons and linear accelerators, the Harwell accelerator programme has been one of constructing machines of existing types, rather than developing new types. The completion of the machines described above marks the end of the programme; for the most part these great tools of research, having been installed, have been handed over to the nuclear physicists in universities and in Harwell to take their place alongside the cloud chambers and Geiger counters as part of the equipment of the laboratories. The exception to this rule is, of course, the further development of the travelling-wave linear accelerator, in which the technological future is full of the most exciting possibilities.

The particle accelerators at Harwell represent a considerable capital investment, and so that the best possible use shall be made of them they are being made available when possible for experiments by university research workers.

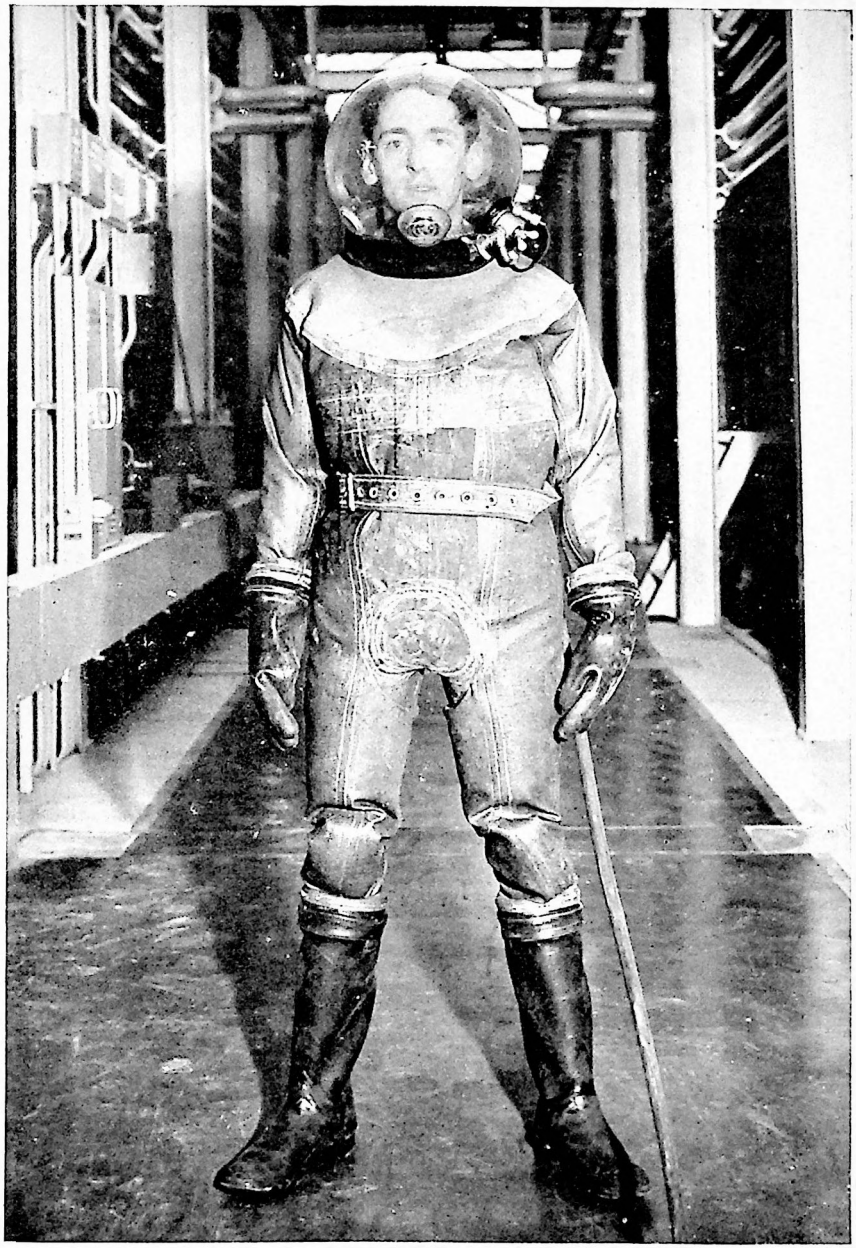
SEVEN

THE PROTECTION OF HEALTH AND THE DETECTION OF RADIATION

The nature of radiation hazards

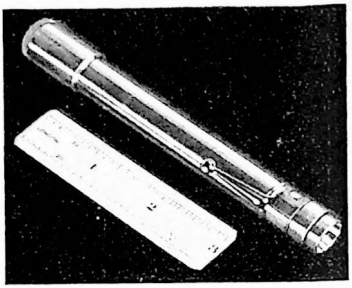
ONE of the major technical problems in all atomic energy work is the protection of the workers from damage to their health by the various kinds of radiation that are inseparable from such work. The dangers are more insidious than most of those confronting the plant engineer; for example there are very few chemical poisons which do not give some indication to the five senses and which would not be stopped by a six-inch concrete wall, but a beam of neutrons from a cyclotron cannot be smelt or heard or seen and requires several feet of concrete to stop it. Moreover, the injury caused by radioactivity may not become apparent for a very long time, sometimes for years, but is nevertheless severe and may prove fatal. Harm may be done either by a single large dose of radiation, or by frequent doses of very much lower intensity, for example by daily exposure in a laboratory. Safety is therefore only attained by constant vigilance, but when such vigilance is properly exercised the protection is complete. Indeed, workers in atomic energy projects are in far less danger of injury from radiation than are other workers from the ordinary hazards of industrial life—burns and scalds, cuts and bruises. In this chapter we shall review briefly the steps taken at Harwell to achieve this result.

The danger which faces the atomic worker arises from the damaging effect upon human tissue of ionizing radiation, whether the ionization be produced directly by charged particles such as electrons or protons, or indirectly by the passage of uncharged neutrons, which cause ionization indirectly by collision with some of the atoms of the tissue. Everyone is continuously exposed to bombardment by naturally-generated radiations from such sources as cosmic rays or the radioactive elements in the earth's crust. The effects produced by radiation depend on intensity and time of exposure; a dose is, in fact, the integrated product of the two. So exposure to a moderate intensity for a long period may do more damage than a much larger intensity which lasts only a short time. The dose may be taken in several ways: by direct exposure to the radiation; by ingestion of radioactive material in food; by absorption through the skin or a wound; or by inhalation of radioactive gas or dust. The last three are the most dangerous, because once the victim has absorbed the active material, probably without knowing it, he cannot escape from the radiations released by it, unless the radioactive material is excreted as a result of the normal body processes. An internal exposure to radiation of this kind will, of course, attack the tissue in the most intimate way possible.

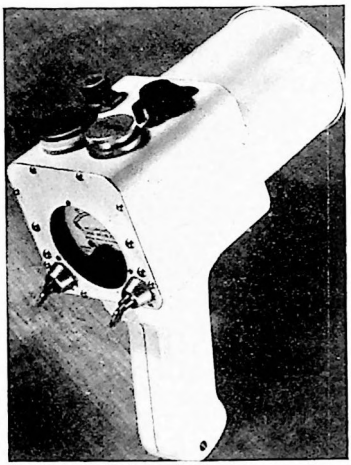


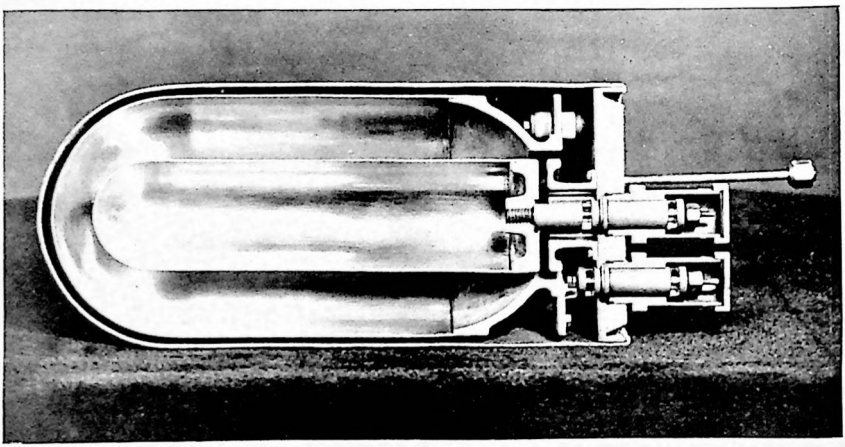
19. The frog suit and helmet worn when clearing cells that have been used for highly-active experiments.

20. Hands-and-feet monitor. Workers must check that they are free from contamination before leaving their laboratories. (*Right*) Pistol-grip dose-rate meter.

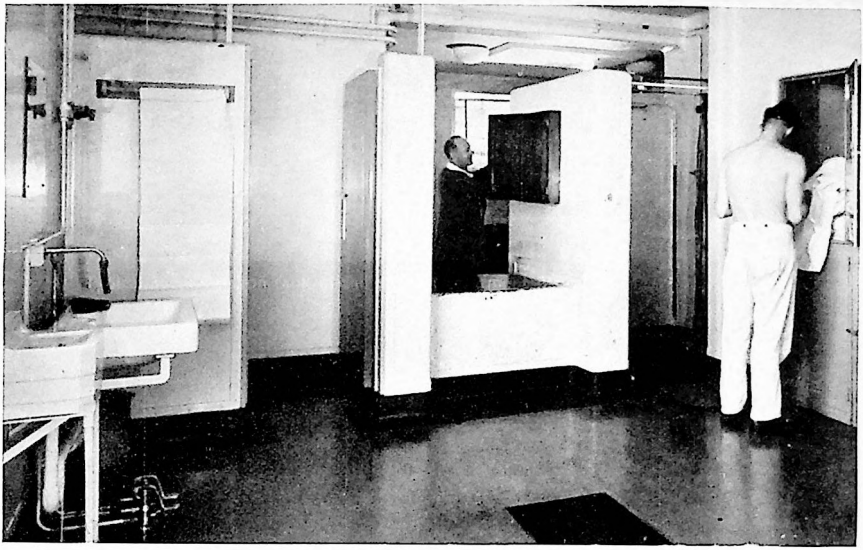


21. The fountain-pen radiation monitor.

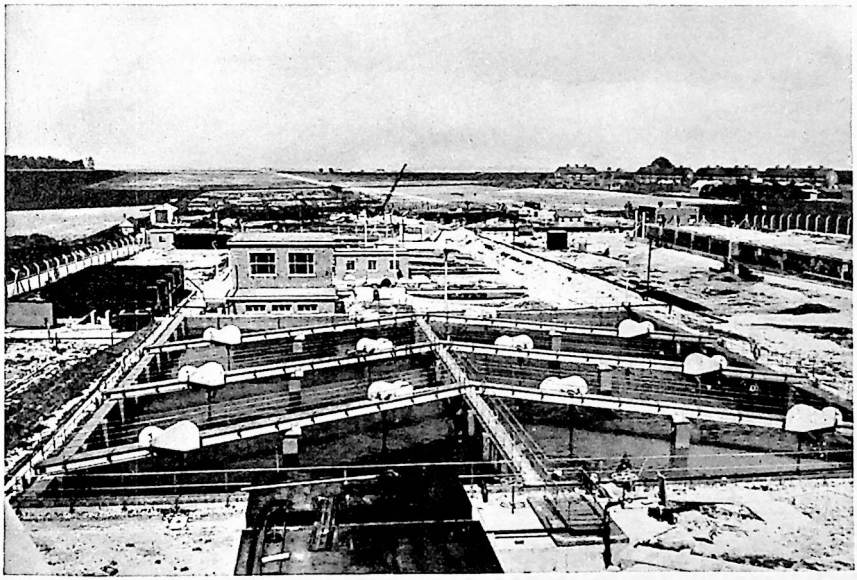




22. Section through a large ionization chamber.



23. The stringent precautions taken to prevent carrying toxic material out of a laboratory are illustrated by this photograph of the vestibule of a beryllia laboratory. The man in the centre is reminded by the barrier that he may not enter until he has changed into laboratory clothes; the man on the right is removing his contaminated clothes before taking a shower. He will emerge from the shower on the far side and there put on his ordinary clothes. Note the foot-operated taps in the wash-basin at the left.



24. Typical 300,000-gallon tank in the effluent treatment plant.

25. Manipulating chemical apparatus in a dry box. The operator, working with his hands in rubber gloves let into the walls of the dry box, is measuring a minute quantity of active solution by means of a micro-pipette. Dry boxes are used for operations involving toxic hazard.

Protective measures

Protection against these dangers is provided by shielding workers from direct radiation or by preventing them from ingesting or inhaling radioactive materials. The aim of protective measures is not so much to prevent absolutely any exposure to the hazard as to reduce the exposure to a level at which it is certain that no harm can ensue. These safe levels (they vary with the nature of the hazard) are specified in terms of what are called maximum permissible levels, or tolerance doses, that is, doses which it is known can be taken safely, and a very great deal of experimental and theoretical work has been, and is being, done on the determination of these tolerance doses. The methods of protection also vary with the hazard. We have seen how thick screens of concrete are erected round reactors and high-energy particle accelerators like the cyclotron, to reduce the direct radiations from them to a safe level. The most dangerous of these direct radiations are neutrons and γ-rays, both of which are exceedingly penetrating; α particles, by contrast, can be stopped by a sheet of tinfoil and β's by a tenth of an inch of aluminium. On the other hand, if an α- or β-emitting substance gets into the body tissues, the particles from it can cause a great deal of damage even although they are absorbed in a comparatively small thickness of tissue. Protection against these hazards is therefore obtained by ensuring that the worker cannot breathe air containing a dangerous concentration, or collect radioactive materials on his hands or skin or clothes. All sorts of precautions from simple gas-masks to the elaborate air-conditioning of the "hot" chemistry laboratory (described in Chapter 8) are used to remove active gases, and persons working with radioactive material wear protective gloves and other clothing. When the material is exceedingly active, the two sorts of precautions are combined and all operations are performed by remote control in screened cells, the manipulations being watched by means of periscopes.

When all the precautions have been taken, however, there still remains the question, have they been effective? Or has anyone inadvertently been exposed to a dose greater than tolerance? To answer these questions and to make sure that there have been no accidental over-exposures, it is necessary to set up, in any atomic research or production organization, an elaborate monitoring and checking service. At Harwell the necessary service is provided by two organizations, the Medical Division and the Health Physics Division. Roughly speaking, the Health Physics Division is responsible for controlling the levels to which workers may be exposed, whilst the Medical Division makes clinical examinations and biochemical tests to ensure that the standard of health is maintained and to detect any damage at an early stage; it also maintains a first-aid service for ordinary injuries and accidents. The Division has a very well-equipped x-ray unit and haematology and biochemical laboratories, staffed by specialists in these branches. The Principal Medical Officer in charge of the Division advises on all aspects of public health on the site, not only those connected with radiation hazards. It should be said here that, although the hazards from radiation are the most dangerous and difficult to deal with, it is of course inevitable that the more common chemical and toxic hazards also are encountered at an establishment like

Harwell. Some of them are unusual insofar as work is done on materials not commonly used in quantity. An example of this is beryllium, which has been found to be highly toxic though not, of course, radioactive. The Principal Medical Officer acts as a liaison officer with the Medical Officers in other establishments of the Ministry and in other Ministries.

Control of radiation levels

The most important part of this work is the accurate measurement of the dose received by each of the persons exposed. This is called personnel monitoring and at Harwell it is done principally by means of film-badges, though use is also made of pocket electrometers. The film-badges are badge-like containers, carried by the people concerned, in which there is a piece of photographic film partly covered by a special lead screen. If the badge is exposed to radiation the film becomes blackened to an extent depending on the dose received; x- and γ-rays are recorded by the portion under the lead filter, β-rays by the rest of the film. The badges are examined weekly and the doses calculated. In the rare event that any shows that the wearer has had a dose greater than a fifth of the tolerance value two actions are taken. First the cause of the radiation exposure is investigated, and secondly a report is made by the Health Physics Division to the Medical Division, who check by means of blood tests that no damage has been done and take any precautionary or therapeutic measures that may be necessary. A new film-badge has recently been developed which will record doses of slow-neutron radiation; in this badge the lead screen is replaced by cadmium. It must not be supposed that all parts of an establishment such as Harwell contain potential radiation hazards. On the contrary there are only a few such areas, as for example round the piles or in the radiochemical laboratories, and these are well defined. They are known as restricted areas and are divided into two classes distinguishable by colours, red and blue; in red areas the radiation intensity may exceed the "maximum permissible level" which the Medical Research Council has defined, in blue areas it must lie between this level and a tenth of the maximum. Film-badges are issued only to people who work in or visit restricted areas. Even so, as many as 1,400 badges are issued every week, and the examination and processing of these is a considerable task.

In addition to monitoring the exposure of individual persons, it is necessary to monitor the radiation level in their laboratories. In all areas where dusty operations are carried out (e.g. uranium machining), or where a spill of radioactive material has occurred or where isotopes of high toxicity are manipulated, surveys are also made for radioactive dust in the laboratory air. Many laboratories have installed continuously-running dust monitors. The levels are found to be some orders of magnitude below the 10-year continous breathing tolerances, except on occasions when a particularly dusty operation is carried out or where a spill of radioactive material has occurred, and in these instances special precautions, such as wearing a respirator, are taken until the contamination has been reduced. The monitoring for contamination of the benches and floors of the laboratories is done by electronic instruments which measure the radiation

intensity and the total dose of radiation that might be received in the vicinity. Fixed installations of this kind are used in the neighbourhood of all major pieces of apparatus which give rise to radiation. Small portable monitors are also used extensively to check the radiation in laboratories or in the neighbourhood of small pieces of apparatus. These portable instruments give only an instantaneous reading on a calibrated scale, whereas the fixed instruments are usually fitted with a recording arrangement as well as an instantaneous indicator. Special monitors have also been designed to determine whether a person has radioactive material on his hands or clothes, or whether benches and equipment are contaminated with it. These so-called contamination monitors are installed particularly in chemical and metallurgical laboratories, where active material is handled, and workers in the laboratories test themselves whenever they leave the laboratory. We shall discuss these monitoring instruments in more detail later in this chapter.

Gaseous effluent from the stacks

The most stringent precautions are taken at Harwell to ensure that no dangerous amounts of radioactive material are dispersed into the atmosphere, especially through the chimneys of Bepo and the "hot" chemistry laboratory. Elaborate filters are fitted to remove active dust and the outflowing gases are continually monitored. In order to ensure that these precautions are successful, fixed monitors have been installed in the grounds of the Establishment and in the surrounding residential areas to record the radiation in their vicinity. If the intensity was ever found to exceed more than a small fraction of the tolerance dose, the pile would be shut down until the cause was found. Another part of these precautions is the use of monitoring and recording vans, which are driven to selected places in the surrounding countryside to make spot checks of the radiation background. Tests by these vans show that all the operations at Harwell cause only a very small change in the natural background downwind from the Establishment. This is quite insignificant compared with the permissible radiation level, which is some 200 times the natural background. There is therefore no possibility of danger to health, but the small variations in background activity are of considerable interest to the scientists whose sensitive Geiger counters may be affected.

These experiments on the dissemination of active gas from the stacks have also included some measurements of the effective height of the Bepo chimney by means of instruments carried in a captive balloon, flown from various points on the Establishment. Since the gases escape from the chimney with a considerable velocity and at a temperature somewhat above that of the surrounding air, it was to be expected that they would rise for some distance before they began to disperse, so that the effective height of the chimney would be considerably greater than its actual 200 ft. The balloon experiments showed that this was in fact so and that the effective height varied with atmospheric conditions and might be as great as 500 ft. The experiments were of importance in connection with the design of the Windscale plant; they are also of fundamental interest to the meteorologist, as they provide experimental data by which to test the theories

of the dispersal of gases in the atmosphere. They are therefore of considerable importance in the study of atmospheric pollution by power stations and industrial gases.

Liquid effluent

An analogous problem to the foregoing is that of the disposal of liquid radioactive waste products from Harwell, the effluent problem. Many laboratory processes produce a large volume of more or less radioactive water: this is especially great in the chemical laboratories but comes from most laboratories in which active material is used. Such waste obviously cannot be poured down the ordinary drain and left to find its way, via the sewage farms, to the rivers and seas. No ordinary sewage farm would be capable of removing the activity and this might be released into the country's rivers and find its way into drinking-water supplies. It has therefore been necessary to take special, and very elaborate, precautions in connection with the disposal of the active effluent at Harwell.

There are really three sorts of liquid effluent at Harwell, two of which are not intended to be active at all. So strict are the standards applied to determine whether or not an effluent is to be classed as radioactive, however, that all the ordinary sewage effluent and all the nominally-clean process water from cooling circuits and the like are treated as if they were radioactive and are passed through the effluent treatment plant. In fact, the activity of these last two effluents is extremely low, since it arises only rarely from the accidental discharge of slightly active solutions down the wrong drain, but no chances are taken and the effluents are treated along with that which it is expected will be active. The active effluent is divided into two classes, moderately active and highly active. The highly-active liquid is not discharged into a drain at all but is collected in vessels in the laboratory and taken to a special storage site. Here the activity of the liquid is measured from time to time, and when it has fallen to a low enough value (as of course it will inevitably do) it is added to the moderately-active part and given the same treatment. In the future it is intended to build a screened treatment plant for this highly-active liquid, in which it can be evaporated to reduce the storage space required. Moderately-active liquid is discharged into a special drain in the laboratories, separate from that carrying the ordinary sewage. These so-called acid-active drains lead into local delay tanks, near the laboratories, which usually have a capacity of 500 gallons or so. When one is full its contents are tested to determine their activity and also their acidity. If the analysis shows that these quantities conform to certain standards, the tank is discharged into the drain and the contents proceed on the next stage of their journey to the river. If, however, the effluent is too active, it is pumped into a motor tanker and removed to the treatment plant, where it is stored in special 12,000-gallon tanks until its activity has decreased sufficiently to allow of its treatment with other effluent.

The subsequent treatment of the effluent takes place in what is known as the effluent treatment plant. A diagram showing the various stages in the treatment is given in Fig. 7. The incoming moderately-active effluent is passed into one

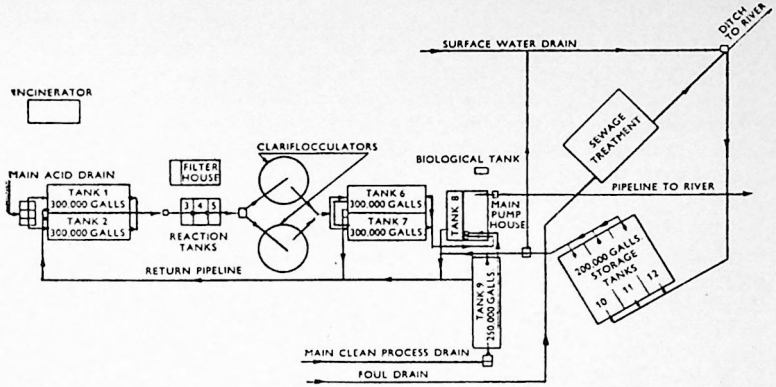


Fig. 7. Effluent treatment plant.

of two 300,000-gallon delay tanks (tanks Nos. 1 and 2). For the present we will ignore the nominally-clean process water (which flows to No. 9 tank on the plant) and the ordinary sewage effluent, and concentrate on the active liquid. This is treated not continuously, but in batches corresponding to the contents of either No. 1 or 2 tank. Although primarily storage tanks, these are so designed and equipped that they can be used for treating the liquid in them. The batch of liquid is stirred in the tank and samples tested to determine the activity and the acidity or alkalinity. The latter properties have to be restricted to a certain range because an excess of either would have deleterious effects on the river life. Because of the care taken to check the local delay tanks before sending the effluent on to the treatment plant, the radioactivity at this first stage is usually low enough to permit the effluent to go forward to the next stage after the acidity has been adjusted. The effluent is drawn from the surface of the liquid in the first tank, leaving most of the solid matter as sludge at the bottom, and passed through three small reaction tanks, in which lime may be added if the acidity is still too great, to two clariflocculators. In these queerly-named devices any residual suspended solid matter is removed. The sludge from the clariflocculators is filtered and dried and the dry radioactive solid stored until its activity decays. The clear fluid from the clariflocculators flows to one of two more 300,000-gallon tanks (tanks Nos. 6 and 7) where it is again stirred and sampled. If the activity and acidity are right permission is given for the tank to be discharged; in this event two other samples are taken, one for the Ministry of Health and one for the Metropolitan Water Board, so that they can check the Harwell results. If the activity and acidity are not right, however, the whole batch is pumped back to tank No. 1 or 2 and the process repeated.

Before reviewing the final discharge process we must return to the clean process water, which we left in No. 9 storage tank in the treatment plant, and to

the ordinary sewage effluent. It was originally intended that the clean process water should be mixed with the effluent which had come through the treatment plant and still further dilute the small amount of activity remaining; the whole was then to be discharged. The ordinary sewage effluent was to have been discharged to a land ditch after the normal purification processes. When, however, it was found that there were traces of activity in these two effluents, it was decided to treat them both in the same way as the active effluent, so now the clean process water is pumped from tank No. 9 to tanks 1 and 2, and thereafter follows the same route as the active liquid and, in its turn, the ordinary sewage effluent. When a batch of effluent has been certified fit to discharge it is pumped to a break tank at the top of a low hill near the Establishment, whence it flows by gravity through some six miles of 18-inch cast-iron pipe to a specially-built weir on the Thames at Sutton Courtenay. This little hill provides a useful natural safety-stop insofar as it would prevent any accidental flow of contaminated liquid into the outflow. During the whole of the discharge samples are taken at the break tank, in the pipe-line and at the outflow. Some of these samples are analysed by Harwell and some are sent to the Thames Conservancy Board for their check. In addition, men periodically put out on the river in a small boat and take samples of the water at various places and also of the mud of the river bottom. These are then checked for activity and analysed chemically to make certain that there is no accumulation of activity. The permitted level of activity has been fixed by the Medical Research Council, in agreement with the Thames Conservancy Board, the Ministry of Health, and other interested bodies. The value is, however, so low that it is detectable only with the most sensitive instruments. The elaborate precautions outlined above ensure that this level is never exceeded, with the result that the effluent cannot possibly afford a hazard directly or indirectly to the public.

The monitoring of the effluent also includes radiochemical analysis. The reason for this is, as we have already seen elsewhere, that certain radioisotopes are especially dangerous because they are absorbed selectively by the body and strong concentrations may be built up in certain organs or structures although the concentration in the effluent is quite small. Actually, it turns out that certain isotopes are so much more dangerous than others that the tolerance doses can be specified in terms of them only, so that a complete chemical analysis is not necessary. Thus the β-emitting strontium 90 is so much more dangerous than other isotopes that the tolerance for all β-activity is specified by the activity of this isotope only. Similarly, α-emitting plutonium sets the limit for α-emitters, though in certain circumstances it is necessary to analyse for uranium and polonium as well. The analytical chemist is faced with some very tricky problems; for example, he may have to determine mere traces of uranium or polonium in the presence of a million times as much calcium and other elements. To do this the radioactive elements must be separated from the other elements and then accurately determined. Much work had to be done by the analytical chemists to find a solution to problems of this kind.

It is worth mentioning that the question of radioactivity is not the only one that arises in connection with Harwell effluent. It is also regarded as a trade waste

and is therefore subject to the provisions of the Thames Conservancy Act of 1932 with regard to the discharge of chemical and oily wastes, and to the content of biological and solid matter. Thus there are other analytical problems besides those outlined, though of course methods of dealing with these are, for the most part, well established.

Tolerance doses; work of the Medical Research Council

We have referred frequently to safe levels of activity and to the tolerance doses upon which these levels are based. The magnitude of the dose of direct radiation, α, β, γ or neutron, which a person can tolerate without danger is now fairly well established and does not vary much with conditions. But the quantity of radioactive material that can safely be ingested or inhaled varies tremendously with the element concerned. This is because some isotopes are absorbed specifically by certain tissues or organs, so that a small quantity of the isotope may build up a very large local concentration. It is therefore necessary to determine experimentally the behaviour of the various elements and isotopes and hence the doses which can be permitted. There is also much to be learned about the effects of very large doses of radiation. This is biological research and therefore the province of the Medical Research Council rather than of the Ministry of Supply. Accordingly in 1947 by arrangement with the Ministry of Supply the Medical Research Council undertook to establish a Radiobiological Research Unit at Harwell. The functions of this Unit are to study the effects of radiations upon biological material and in particular to investigate means of protection against the harmful effects produced by ionizing radiation. The work in progress is briefly reviewed in the Annual Reports of the Medical Research Council and will not, therefore, be discussed any further here.

Monitoring instruments and electronic devices

To perform the various monitoring functions several different sorts of instrument are required, the design of which is a highly specialized business. This design work is done by the Electronics Division at Harwell, who usually make prototype equipments from which industrial manufacturers develop models for production in quantity. It is not possible to give more than a brief résumé in this account of the work of the Electronics Division; some of the equipments developed have been described in the technical press and it is hoped to give a detailed account of certain others in future publications in this series.

Health monitors fall into two broad classes. In the first are those designed to measure the total dose of radiation received by the instrument; these are used for personnel and for area monitoring. In the second class are contamination monitors, designed to measure the intensity of radiation, or the dose received in unit time. The simplest dose-meter is the film-badge.

In some circumstances, however, this may not be the best instrument for personnel monitoring, especially as there is some delay, in processing the film, before the dose can be determined, and a considerable organization is required if any number of films is to be processed. These objections are of particular weight

in a civil defence organization for use against atomic bomb attacks. For these and similar requirements an instrument called the pocket electrometer has been developed in various forms. This instrument is essentially a condenser ionization chamber. Any ionizing radiation passing through the chamber causes the air in it to become partly conducting, with the result that some of the charge is lost from the central conductor. The amount of charge lost is determined by connecting the chamber to an electrometer. For many purposes, especially in connection with civil defence, a form of instrument is used which contains its own electrometer. This instrument, which is called the fountain-pen monitor from its size and appearance (Plate 21), makes use of an up-to-date version of the old-fashioned gold-leaf electroscope, in which the fragile gold leaf is replaced by a fine, but exceedingly rugged, gold-plated quartz fibre.

Area monitors could be made on the same plan as the fountain-pen monitor just described, but because size and weight are usually of secondary importance in this application, the quartz-fibre electrometer is often replaced by a valve electrometer. The use of these valves (basically the same as ordinary wireless valves) has the advantage that the indication of dose can be given on an ordinary current-measuring meter. Small-area monitors can be operated from self-contained batteries. When the monitor is always to be used in the same place, as for example in a chemistry laboratory, it is preferable to run it from the electric supply mains. Various monitors of this type have been developed, some fitted with clocks driven from the monitoring circuit, by means of which the dose rate as well as the total dose can be measured.

In contamination monitoring, as in area monitoring, both portable and fixed instruments are needed, but here the requirement is to determine dose-rate or intensity rather than total dose. The smallest portable instrument in this family is the so-called pistol-grip dose-rate meter type 1043a (see Plate 20). Light enough to be held in one hand and pointed at the suspected source of radiation, this instrument contains an ionization chamber, electrometer valve, batteries, and indicating meter calibrated in milliroentgens/hour. Larger instruments of the same type are made, but in order to obtain the sensitivity required for contamination monitoring it is usually necessary to use the more elaborate but much more sensitive Geiger-Müller counter and its associated equipment. Monitors of this last type are used, for example, in the so-called hands-and-feet monitor, illustrated in Plate 20, with which traces of radioactivity can readily be detected on the hands or clothes of a worker. Another application is to the door-post monitor, in which a long Geiger-Müller tube is placed on the door-post of a laboratory to cause an alarm to sound if any contaminated person passes through the doorway.

The Geiger-Müller tube has been introduced here as a component in another type of monitor, but it is of far more general importance than that. Indeed it is not too much to say that nuclear physics could not have advanced to its present state without the Geiger-Müller tube, and that this instrument ranks with particle accelerators among the fundamental tools of the nuclear scientist. The Geiger-Müller tube owes its importance to the fact that it produces a separate response, in the form of a pulse of current, to every ionizing particle that passes

through it. The size of the pulse of current is independent of the energy of the incident particle. Therefore, within the limits imposed by instrumental defects, the tube may be used to count the total number of particles emitted from a source in a given time, however weak or strong the source and whatever the radiation (α, β or γ) given off by it. Such a count will give a measure of radioactivity in all sorts of circumstances, and the accuracy of the measurement can readily be determined. Moreover, by the use of special electronic circuits it is possible to count at extremely high rates, and to record the counts on paper if desired. For research purposes several standard types of counting equipment have been developed at Harwell, in addition to the, usually rather simpler, dose-rate meters for contamination monitoring. No attempt will be made to describe these equipments in this account, but a list of papers by Harwell writers on the subject is included in an Appendix.

The personnel and other monitors just described are usually designed to work on γ radiation (which is one of the most penetrating) and, by means of a suitable window, on β-rays. Alpha particles are so easily absorbed that it is not necessary for the simpler sorts of monitor to be able to detect them; contamination monitors may, however, have to be sensitive to α particles and this can readily be arranged by replacing the standard Geiger-Müller tube by a special α counting tube. Monitoring for neutrons is, however, of great importance, especially in the neighbourhood of piles and particle accelerators, but none of the devices so far described is sensitive to them. The difficulty is overcome by filling ionization chambers with a compound of boron, usually boron-trifluoride, which is disintegrated by neutrons with the release of an ionizing particle. The ionization produced by this particle causes a pulse of current in the ionization chamber which is amplified and counted in the same way as the pulses in a Geiger counter. Boron trifluoride chambers are used not only in neutron monitors but also to determine neutron intensities in the pile and in various experiments with neutron beams.

In addition to developing many novel counting equipments, the Electronics Division is doing a great deal of research into new kinds of counters. A long series of experiments with new kinds of electrodes and new gas fillings for Geiger counters is leading to tubes having much longer lives, with greater stability and lower operating voltages.

Other important experiments are concerned with an entirely different type of counter, the scintillation counter, in which the ionizing particle is detected not by the ionization which it causes in a gas, but by the flash of light which it produces in certain solid crystals. In principle this is the oldest method of quantitative particle detection, but recent developments in the type of crystals used, and in the application of photoelectric (photomultiplier) tubes to the detection of the light flashes, have led to great advances in the method. Scintillation counters are particularly suitable for counting α particles and γ-rays in circumstances in which the efficiency of Geiger counters is not high.

EIGHT

FUNDAMENTAL RESEARCH WORK

EARLIER in this account we commented on the difficulty of disentangling one programme from another, of deciding whether, for example, a piece of work should be described under the production programme or under the reactor programme. Even greater difficulties present themselves when we try to distinguish fundamental research from that which is linked more or less directly with an application. Nevertheless it is possible to distinguish in the Harwell programme a good deal of work which is not directed to the solution of an immediate problem in the production, isotope, or reactor programmes. It may consist of fundamental research into the nature of the forces which hold atomic nuclei together; it may be rather long-range research which if successful would enable new and important projects to be initiated; or it may consist of rather basic studies of phenomena which may be of importance in the future development of atomic energy. This fundamental research is essentially laying the foundation for the applied researches and the technological development of five or ten years ahead. It is necessary not only for this purpose but to keep an establishment alive. The existence of this programme enables scientists to move from applied work to fundamental work and back again. They are thereby enabled to publish work, to establish their scientific reputations, and to escape that sterility which descends on so many scientists in the latter part of their career.

Much of the pure research at Harwell springs from work for applications. Much indeed is directly for applications, because so little is known about things like the effects of radiations that it is necessary to study the fundamental processes before more than the barest outline of a practical application can be considered. Other investigations, begun in connection with specific applications, have shown effects of great interest, though not relevant to the immediate problem, and the research worker has been encouraged to pursue these new lines for their own sake.

A certain amount of pure research is done at Harwell because the experiments involved require the use of the major installations which are available there and nowhere else in the United Kingdom—the piles, the accelerators, and the "hot" laboratories. These facilities are made available to workers in universities who can come to Harwell for short periods to carry out experiments. "Harwell Research Fellowships" are also offered to enable experienced graduate students to come to Harwell for several years to work with these tools.

We shall describe examples of the work in these different categories under the three broad headings of physics, chemistry, and metallurgy. It is not possible in this account to report on research in every subject, and engineering, biology and chemical engineering have been left for a subsequent publication. Even in one subject the treatment cannot be complete; in chemistry, for instance, some

examples are given of research in the inorganic, analytical and radiation groups, but nothing is mentioned of the organic, physical and radiochemistry groups. These omissions will also be remedied in later accounts.

PHYSICS RESEARCH

As is to be expected, the greater part of research in fundamental physics at Harwell is concerned with the physics of the nucleus of the atom, although there is also a good deal of work on the properties of aggregates of atoms and their behaviour when irradiated.

The properties of the atom as a whole have been studied for many years now, and precise ideas about its structure have been built up; thus, to give an example, its behaviour as an emitter of light can be predicted quantitatively with considerable accuracy. Far less is known, however, about the structure of the atomic nucleus. Indeed, it may be said that knowledge of the structure of the nucleus is at present at the same stage as was knowledge of the outer atom thirty-five years ago. The general structure is visualized as a closely-packed collection of neutrons and protons having many of the properties of an exceedingly dense liquid, but the details of this structure, and in particular of the forces that hold it together, are by no means clear. The question of these binding forces is especially difficult. The protons in the nucleus have all the same charge, and consequently they will repel one another with a force that will be very great because they are so close together. It follows therefore that there must be some other, and still greater, force counteracting the electrostatic repulsion and keeping the nucleus together as a stable entity. Experiments are being carried out with the high-speed protons and neutrons produced by the Harwell cyclotron to study the nature of nuclear forces. The experiments may be visualized as a game of nuclear snooker. An atomic nucleus of beryllium may be thought of, for example, as a snooker pool of 4 red balls (protons) and 5 white balls (neutrons). A very high-speed proton or neutron is fired into the pool and knocks on one or more of the protons or neutrons in the nucleus. In practice a very large number of protons or neutrons are fired into a large number of nuclear pools and the physicist observes how many protons or neutrons come out at different angles. He then studies the statistics of the result and is able to compare this with the results he would have expected from a particular theory of nuclear forces. The results obtained so far have shown that when protons collide with protons they behave almost exactly as very minute elastic billiard balls would behave in collision; when protons collide with neutrons, on the other hand, the results are quite different—and this is certainly not due to the fact that the neutron is uncharged. When protons collide with heavy hydrogen nuclei which contain a proton and a neutron, the results are quite different again.

When the speed of the proton in this game of nuclear billiards is increased still further, new transient particles known as mesons appear to come out of the collision. They may be thought of perhaps as sparks struck in the intense fields of force which operate when the two nuclear particles approach each other. Meson production is evidently closely connected with the nature of nuclear

forces, but theoretical physics has not so far been able to develop any satisfactory detailed theory of the connection. Here again experiment must lead on theory.

Another important practical and theoretical aspect of the study of nuclei is the magnitude of their so-called energy levels. The study of the energies of particles and γ-rays emitted from radioactive nuclei, or from nuclei bombarded by particles of known energy, gives much information about the structure of the energy levels inside the nucleus. The linear accelerator which was described on page 53 and the Van de Graaff generator are used to produce neutrons of known energy which can then be fired into other nuclei to set them into vibration and so allow their energy levels to be determined. The linear accelerator produces comparatively slow neutrons. The Van de Graaff generator provides faster neutrons—moving with speeds of about 10^6 kilometres a second—but still much slower than the neutrons produced by the cyclotron.

Information on the nuclear energy levels of the different isotopes of uranium and plutonium, and on elements such as carbon, beryllium, aluminium and zirconium, used in the construction of reactors, is important in the technological programme.

The nuclear reactor is, of course, the newest research tool to come into the hands of nuclear physicists, and the Harwell piles are the only instruments of this kind in the United Kingdom. We shall therefore first consider the applications of the reactor to research, with some of the experiments being done with them at Harwell. We shall then review briefly one or two other experiments of general interest.

The nuclear reactor as a research tool

The nuclear reactor can be used for experiments in physics in, broadly, three different ways. In the first, changes in the reactivity of the reactor are used to measure such things as absorption cross-sections of nuclei; in the second the reactor is used as a nuclear furnace in which to subject substances to very strong fluxes of neutrons, to cook them with neutrons instead of heat radiation; in the third it is used as a source of strong beams of neutrons with which to study the consequences of collisions between neutrons and the atoms of matter. For all purposes where slow neutrons are needed, the reactor running at high power has the decisive advantage of producing far more copious streams of neutrons than can be obtained by other means.

Measurements involving the reactivity of the pile

The first of the methods mentioned above depends upon the fact that, when a reactor is running at constant power, the insertion of extremely small amounts of neutron-absorbing material will cause the power to decrease, or their removal cause it to increase. For example, the change in the amount of nitrogen, present in the air in the pile, produced by a change in atmospheric pressure of as little as 0.05 mb. will change the power by a measurable amount; the nuclear reactor is, in fact, one of the most sensitive barometers known to man, if also one of the most expensive.

One application of this method is to the measurement of the neutron absorption cross-section of elements. Reference has already been made to the importance of such measurements in connexion with the construction of piles. There are two methods of making the measurements. In the first a sample of the element to be studied is put into the reactor and the movement of the fine control rod necessary to compensate for its effects is determined; the sample is then removed and replaced by an element of known cross-section, boron for example, and the corresponding movement of the control rod for this standard is compared with that for the unknown. A better method is that known as the swing method, in which the sample is pulled in and out of the pile in a regularly-repeated cycle by a device known as a pile oscillator. The oscillations of the sample through the pile (which usually have a period of about 20 sec.) cause corresponding oscillations in the power level and hence in the current in ionization chambers in the pile; these current oscillations, after amplification, are recorded on a recording voltmeter in terms of changes in k of the pile. The cross-section may either be deduced from this record, or be determined by comparison with the record produced by a standard element. The method has the advantages that the result is the average of many cycles, and that the effects of random fluctuations in power level are eliminated. Many determinations of cross-sections have been made by this method in Gleep.

Bombardment by pile radiations

The use of the pile as a neutron furnace has been referred to in connection with the reactor programme, for which it is very important to know what will happen to structural materials when they are exposed to strong fluxes of neutrons. The kind of thing that occurs may be illustrated by reference to the moderator materials, graphite and beryllium. Like many other substances these materials have a crystalline structure.

Now when fast neutrons pass through a crystal lattice they knock some of the atoms out of their positions into the interstices of the lattice. For example, it has been calculated that a neutron having an initial energy of 2 MeV, in the process of being slowed to thermal energy in a beryllium moderator, displaces about 500 beryllium atoms. The result of these displacements is to change many of the properties of the material. In particular the electrical and thermal conductivity and the elasticity and other mechanical properties may be affected. The technological importance of these changes is obvious, and from the purely scientific point of view they are of interest since a study of the history of the displaced atoms would throw light on the forces that maintain atoms in their positions in crystalline lattices and on the mechanism of thermal and electrical conduction.

Experiments at Harwell, by T. M. Fry and others, include studies of the effects of irradiation on the conductivity of semi-conductors, pure metals, and alloys; on the colour and fluorescence of diamonds and other insulating crystals and glasses; and on the structure of materials revealed by x-ray diffraction. Measurements by R. Berman at the Clarendon Laboratory have shown a large decrease in the thermal conductivity at low temperatures of a quartz crystal as a

result of irradiation in the pile indicating that the crystal is progressively changed into a quartz glass.

It is expected that this work will add to our understanding of the solid state of matter. It is perhaps worth remarking that these experiments differ from most of those done with the pile in being concerned with assemblages of large numbers of atoms, instead of with single atoms, such as are the main concern of nuclear physicists.

The pile as a source of neutron beams

The third broad classification into which experiments with the reactor fall is its use as a source of beams of neutrons. Usually these will be beams of slow neutrons which may be obtained from the thermal column, mentioned in Appendix B. This beam will be diffuse but can readily be collimated by means of cadmium tubes to produce a beam of width less than 1°.

One experiment done with neutrons from the thermal column of Gleep has been the study by Flowers and others(1) of the transformation of the light isotope of helium, mass 3, into tritium (the hydrogen isotope of mass 3) by capturing a slow neutron. The reaction may be represented by the equations:

$$He^3 + n \longrightarrow He^4 \longrightarrow H^3 + p$$

In the experiment a pressure ionization chamber was filled with atmospheric helium, of which only 1.2 parts in ten million are helium 3. The chamber was placed in the thermal column and the protons produced by the reaction were detected and measured on an electronic pulse analyser. Their energies and numbers were compared with those from the transmutation,

$$N^{14} + n \longrightarrow N^{15} \longrightarrow C^{14} + p$$

Using the known cross-section of 1.7×10^{-24} cm^2 for the latter reaction, the cross-section for the helium reaction was found to have the very high value of $(3{,}700 \pm 250) \times 10^{-24}$ cm^2.

Neutron diffraction

The energies of the neutrons in the beam from the thermal column are not all the same. Consequently when they are used to determine, for example, cross-sections the results obtained represent an average value for the range of energies. It is however often necessary to know how the cross-sections vary with energy, and this of course requires that they shall be measured with neutrons of several different, but sharply defined, energies, in fact by using beams of mono-kinetic neutrons. Such beams can be obtained from pile neutrons by taking advantage of the phenomenon of neutron diffraction. According to the ideas of wave mechanics, the motion of all elementary particles, including the neutron, is

(1) For complete reference see Appendix C.

associated with the motion of a wave having a wavelength related to the momentum of the particle by the expression, due to de Broglie,

$$\lambda = \frac{h}{p}$$

where λ is the wavelength, and p the momentum, of the particle, and h is a constant of nature. For thermal neutrons this expression gives wavelengths of the order of 2.10^{-8} cm. It follows then that neutron waves will be diffracted by a regular array of atoms in a crystal, just as x-rays are. To obtain a beam of monokinetic neutrons in this way, a parallel beam of thermal neutrons from a pile is allowed to fall at a glancing angle on a crystal of, for example, calcium fluoride; the energy of the neutrons in the beams diffracted from the crystal will depend on the angle of diffraction, so that beams of different energies in the thermal range may be selected by choosing the proper angle to the crystal. This device is known as the crystal spectrometer.

In cross-section measurements, a sample of the substance under investigation is placed between the crystal and a neutron detector, such as a boron-trifluoride chamber. The absorption of a known thickness of the substance can then be determined for neutrons of different energies by altering the angle of the crystal. The cross-section so obtained is the total cross-section, i.e. absorption plus scattering cross-section; for strong absorbers like boron, the total cross-section is effectively the same as the absorption cross-section. Using this technique, measurements have been made at Harwell on boron, which is of particular interest because it is so often taken as a standard, and on many other elements(1).

An alternative instrument for obtaining mono-energetic beams of very low energy neutrons is the mechanical velocity selector. This consists, in principle, of a rotating shutter which intercepts a beam from the thermal column, and a detector placed some distance from the shutter. As the shutter spins round it is transparent to neutrons for a very brief interval in each rotation, so allowing short bursts of neutrons to be transmitted. The fastest neutrons in each burst will reach the detector first, and slower ones later. By operating the detector at a given interval after the burst is transmitted, neutrons of a given known velocity can be selected. If a specimen is now placed in the beam, some neutrons will be absorbed, and the total cross-sections can be measured as a function of velocity.

Reverting to the topic of neutron diffraction, it must not be thought that the sole application of this phenomenon is to the production of mono-energetic beams. The technique offers a powerful new tool for the determination of crystal structures, in which field it forms a useful extension of the x-ray technique. The difference between x-ray and neutron diffraction arises mainly from the fact that x-rays are scattered by electrons and the intensity of the scattered electrons increases roughly as the square of the atomic number of the scatterer, whereas neutrons are scattered by nuclei, and the scattered intensity is more or less the same for all atoms. This means that neutron diffraction will be very useful for studying the structure of substances containing some light and some very heavy atoms, such as hydrogen atoms in some organic compounds, or an inorganic

(1) See Appendix C.

compound like lead oxide. When x-rays are used to study such substances, the reflections from the light atoms are swamped by the much stronger reflections from the heavy atoms; if neutrons are used, each sort of reflection would have about the same intensity. Work along these lines is being pursued at Harwell by J. Thewlis and G. E. Bacon.

We must turn our attention now from experiments in which the Harwell piles are primary tools to some which are interesting for other reasons. The first of these will illustrate the employment of particle accelerators in nuclear physics.

The photodisintegration of nuclei

Atomic nuclei can be disrupted by high-energy x-rays, and the Harwell synchrotron, which produces x-rays of up to 23 million volts, has been used for such experiments.

When uranium is bombarded by these x-rays, fissions are produced and about ten times as many neutrons as fissions are observed. Occasionally also—once in about 300 fissions—the uranium nucleus divides into three particles, a helium nucleus being left behind when the nucleus divides into two fragments. This helium nucleus is then repelled from the two fission fragments and acquires an energy of about 20 million volts. The study of these processes can help to decide between the various models which have been suggested to explain fission—one particular hypothesis of interest treats the nucleus as a liquid drop becoming unstable and dividing into two unequal fragments.

When the x-rays fall on to light nuclei they have been observed to eject protons, deuterons, tritons, helium nuclei, and nuclei of beryllium. Carbon can be split up into three helium nuclei; oxygen into four helium nuclei. The nuclei can be ejected in different states of excitation. For example, nuclei of beryllium 8 have been observed having energies of 0.1 and 3.0 million volts of excitation.

RESEARCH IN CHEMISTRY

The impact of the discovery of nuclear fission (which was made by chemists) upon fundamental chemistry has been nearly as great as upon fundamental physics. In the first place, it has widened the field of radiochemistry, that is the study of the chemistry of radioactive atoms, presenting it with a vast number of new radioactive elements and isotopes and demanding from it a considerable extension of its techniques. Then it has focused attention upon the hitherto-neglected chemistry of the heavy elements, especially uranium and thorium, and, moreover, has added to them a whole series of artificially-created elements, heavier than any known in nature, viz. neptunium, plutonium, americium, curium, berkelium and californium(1).

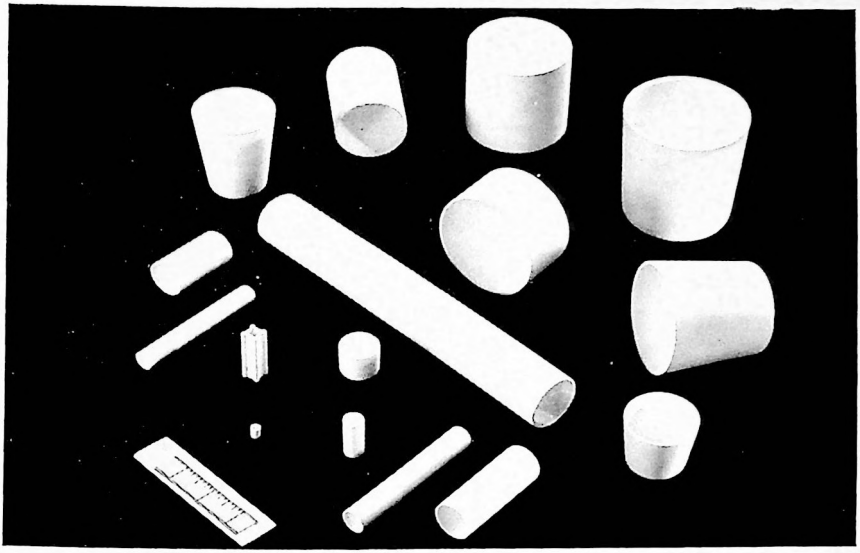
Finally, the technical requirements of pile design and of the separation of fissile material have raised new fundamental problems in radiation chemistry and have led to advances in the understanding of solution chemistry and ion exchange phenomena, and to extensions in the techniques of chemical analysis.

(1) The atomic numbers of these elements are 93, 94, 95, 96, 97 and 98 respectively.

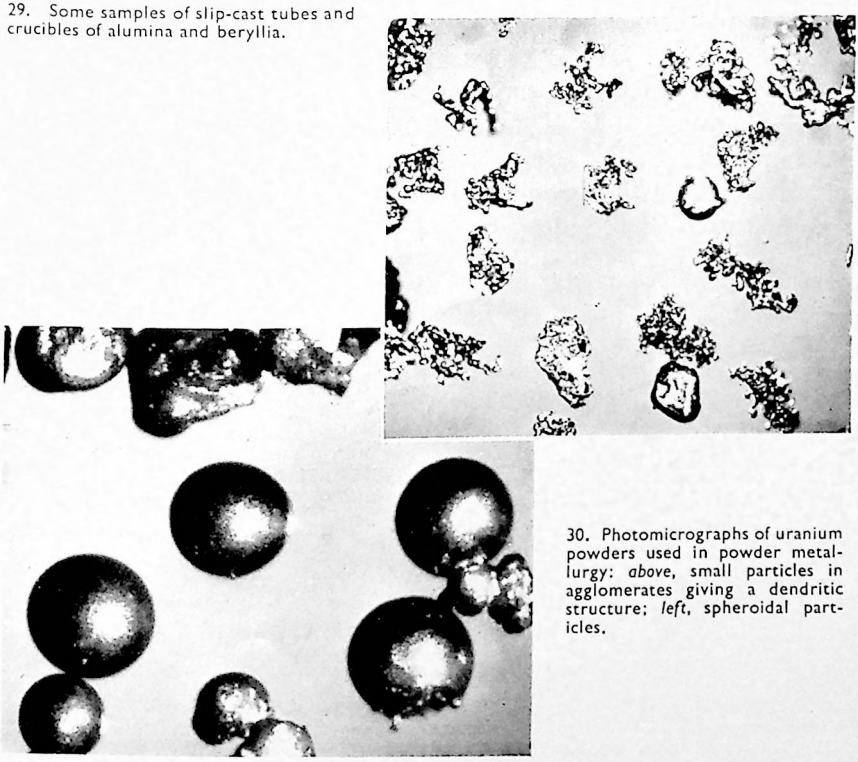
26. The 30-MeV synchrotron, showing the donut being removed.

27. A general view of the radiochemical laboratory, building 220.

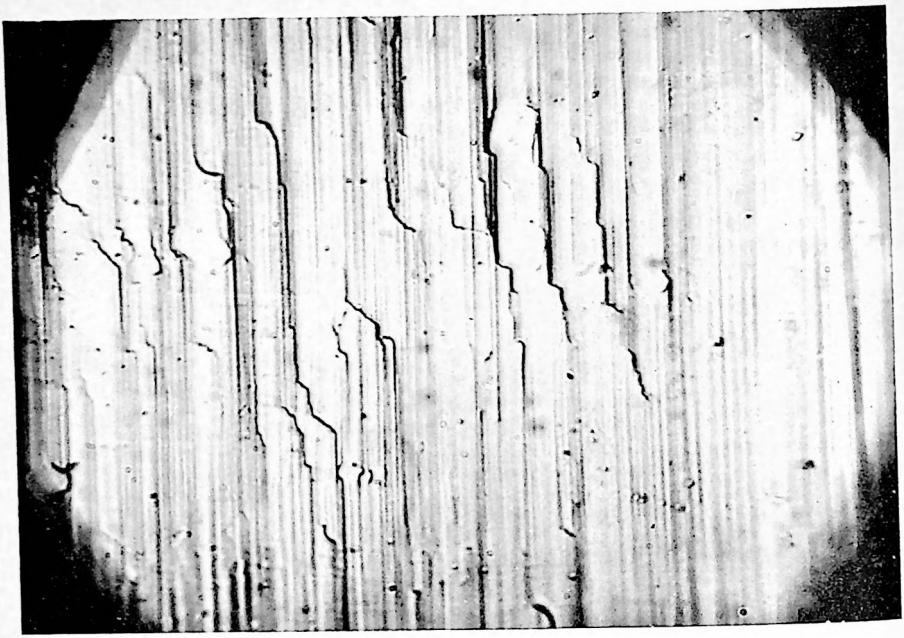
28. Interior of a laboratory in the radiochemical building 220.



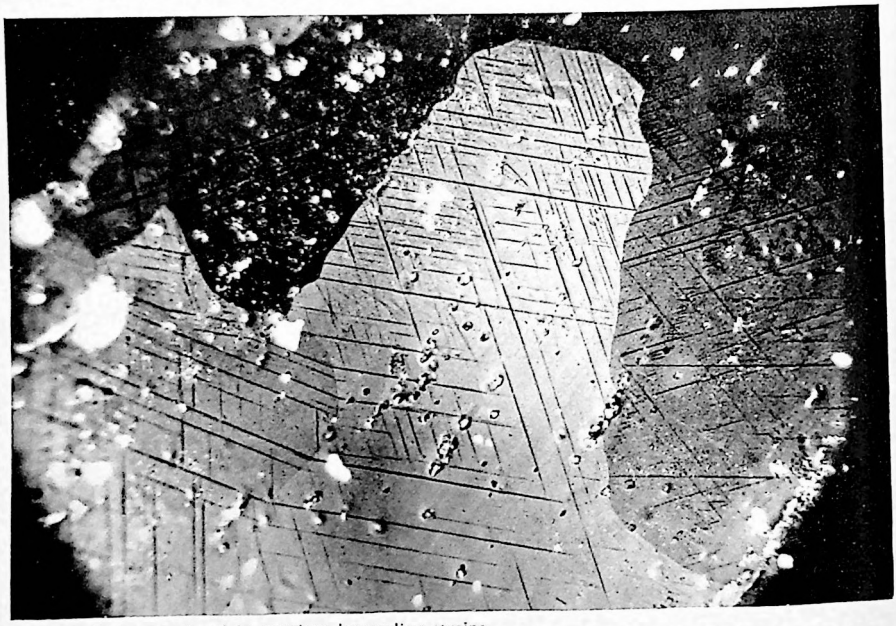
29. Some samples of slip-cast tubes and crucibles of alumina and beryllia.



30. Photomicrographs of uranium powders used in powder metallurgy: *above*, small particles in agglomerates giving a dendritic structure; *left*, spheroidal particles.



31. Slip lines on a lightly-stretched uranium crystal.



32. Twins produced in uranium by cooling strains.

Work is going on at Harwell in all of these fields; much of it is of course secret, but we shall discuss here some of the unclassified (i.e. non-secret) work, especially in the chemistry of the heavy elements and in radiation chemistry.

The fundamental question which has been raised by the discovery of the transuranic elements is, how do they fit into the periodic table of the elements? The answer to this question depends upon the similarities in chemical behaviour which exist between these elements and those of lower atomic number; it therefore involves detailed investigations into all aspects of their chemistry. These investigations, moreover, cannot be limited to the transuranic elements; the naturally-occurring elements immediately preceding them in the periodic table, actinium, thorium, protoactinium and uranium, have also to be studied because, although they have been known for many years, their chemistry is still not fully understood and many conflicting views about it have yet to be resolved. For these reasons, among others, research is being done at Harwell upon the chemistry of thorium and uranium as well as of plutonium and other transuranic elements.

The question of similarities between elements turns upon the arrangement of electrons in the outer orbits of their atoms, i.e. upon the electronic configuration of the valence shells. Evidence about these configurations may be obtained from many sources—the valencies of the element in different chemical compounds, its magnetic properties, the arrangement of its atoms in crystal lattices, spectroscopic observations, and so forth—and observations on all these matters have to be considered before the configuration can be determined. By the term electron shell is meant one of the groups into which fall the system of planetary electrons surrounding an atomic nucleus; each shell or group contains electrons having energies considerably different from those of other shells, but electrons within the same shell have energies, and describe orbits, which are of the same order of magnitude though they differ measurably from one another in a manner explicable by the quantum theory. Each shell can hold up to a certain maximum number of electrons, determined by quantum conditions; when any shell is full further electrons can be added only in the shell of next highest energy, which is farther out, geometrically, from the nucleus. In the heavy elements, however, the outermost shells are so far from the nucleus that they do not differ very greatly in energy, a fact which considerably complicates the process of determining precisely which shell is being filled. To use the standard nomenclature, it is possible that either the $6d$ or the $5f$ shell is being filled in the transuranic elements. If the first hypothesis were true, these elements would be part of a series analogous to the transition groups like the platinum metals and rhenium. It has, however, been unambiguously established that neptunium and plutonium have no similarity to these elements. It is inferred therefore that they belong to a transition series in which the $5f$ levels are being filled. Since this is analogous to the rare earth or "lanthanide" series, it has been called the "actinide" series. The question then arises which is the first element in this new series, i.e. at what atomic number do the $5f$ levels first become tenanted? It has been suggested by some workers that the series begins with actinium, and is strictly analogous to the rare earth series which begins with lanthanum. An alternative, and now

more generally accepted, view is that the elements before uranium are not in the series but that the first member is uranium itself, even though curium, the seventh element after actinium, may perhaps have seven 5*f* electrons. Although the weight of chemical evidence supports this view, the question is not yet settled unequivocally; we shall consider now some of the Harwell work which bears upon it, particularly that done by the inorganic chemistry group under J. S. Anderson and by the radiochemistry group.

The chemistry of thorium

The preparation and study of thorium compounds of low valency, by R. W. M. d'Eye of Anderson's group([1]), has indicated strongly that the occupation of 5*f* levels certainly does not begin before protoactinium, the element next above thorium in the periodic table. At the time the work was begun no compounds had been described which were derived from the lower valency states of thorium, i.e. lower than quadrivalent compounds such as thorium oxide (ThO_2) and thorium tetra-iodide (ThI_4). D'Eye developed an experimental technique by means of which the tetrahalides (thorium tetra-iodide, tetrabromide and tetrachloride, ThI_4, $ThBr_4$, $ThCl_4$) could all be reduced by metallic thorium; in this way the compounds thorium tri-iodide, tribromide and trichloride (ThI_3, $ThBr_3$ and $ThCl_3$) of trivalent thorium, and thorium di-iodide, ThI_2 (and probably $ThCl_2$) of bivalent thorium, have been obtained([2]).

These compounds are completely analogous in physical and chemical properties to the lower halides of zirconium and hafnium. The crystal structure of thorium di-iodide (ThI_2) has been worked out completely by the method of radial distribution function and shown to have the cadmium di-iodide type layer lattice; by the same method the crystal structure of thorium tribromide ($ThBr_3$) has been partly worked out. The interest of these structures lies in the fact that thorium tribromide is definitely not iso-structural with the tribromides of lanthanum, uranium and plutonium, and that the co-ordination number of thorium in both compounds appears to be 6 (octahedrally arranged). If the unused valence electrons were in 5*f* levels, thorium tribromide would almost certainly be iso-structural with lanthanum tribromide. Furthermore, the octahedral configuration in a highly-polarized structure points to the utilization of hybrid octahedral wave functions, involving *d* electrons. These observations lead to the conclusion stated above, viz. that in the heavy elements the occupation of 5*f* levels certainly does not begin before protoactinium.

Uranium oxides

A study of the oxidation of the lower oxide of uranium UO_2, made by K. B. Alberman, also of Anderson's group, has revealed a complex system of intermediate oxide phases which bears distinct resemblances to the molybdenum and tungsten oxide systems. Oxides of known composition were prepared from very

([1]) See Appendix C.
([2]) Similar observations were made concurrently by Hayek in Austria.

pure uranium dioxide UO_2 by oxidizing it in air or oxygen in a thermostatically-controlled oven at temperatures between 120° and 250° C(1). The composition was calculated from the increase in weight.

UO_2 oxidizes at very low temperatures (at or below 100° C., depending on the particle size); the reaction has the kinetic characteristics of a process involving diffusion of oxygen atoms through the UO_2 crystal lattice, and forms, at temperatures below 230° C., a metastable phase of widely variable composition. Between the composition limits $UO_{2.00}$ and $UO_{2.20}$ approximately, the oxide retains the cubic symmetry of UO_2 (fluorite structure), and shows no appreciable change in cell dimensions. The limit of composition in low-temperature oxidation is close to $UO_{2.30}$; oxides of composition between $UO_{2.20}$ and $UO_{2.30}$ are tetragonal, the departure from cubic symmetry increasing progressively from $c/a = 1.000$ at $UO_{2.20}$ to $c/a = 1.032$ at $UO_{2.30}$.

Magnetic susceptibility measurements

Reference has been made to the fact that information about electron configurations can be obtained from measurements of magnetic susceptibility, i.e. the quantity which measures the extent to which an element is attracted or repelled by a magnetic field. This is so because an electron moving with very great speed in its orbit round a nucleus behaves in the same way as a conductor carrying a current and when placed in a magnetic field is acted on by a force, just as the conductor would be, the atom being either attracted to or repelled from the region of maximum magnetic field strength. The susceptibility may thus be measured by hanging a sample of the compound under investigation from the axis of a very sensitive balance, between the poles of a powerful magnet, and measuring the force produced, when the magnet is switched on, as a change in weight.

Using this principle, measurements of the susceptibilities of heavy elements have been made at Harwell by J. K. Dawson. Because the changes in weight expected are very small, Dawson used a particularly sensitive type of balance made from fine quartz fibres fused together, which is sensitive to about one hundred-millionth part of a gram. A sample on which measurements are required is hung from the balance beam and a magnet, giving a field of about 2,500 gauss between two 1-inch diameter pole-pieces, is moved in steps in a vertical direction, so that the sample appears to move through the centre of the pole-gap. At each step a new balance reading is taken and when the results are plotted they show a maximum and a minimum, the difference between which is a measure of the magnetic susceptibility.

The measured susceptibility of uranium tetrachloride at room temperature is $3{,}800 \times 10^{-6}$, which agrees with the $5f$ configuration rather than the $6d$. Similar measurements in the United States on neptunium, plutonium and americium, and others in progress at Harwell, have shown that here also the incomplete shell is most probably $5f$ (which should be capable of holding fourteen

(1) See Appendix C.

electrons, leading to elements far heavier than those which it has been possible to synthesize so far). However, for thorium (preceding uranium by two places in the periodic table) preliminary measurements have shown that the compound thorium tri-iodide has a single electron in the 6*d* shell. This is another piece of evidence for the view that there is change-over from one configuration to the other between thorium and uranium, and certainly not below thorium, and hence that the new elements neptunium, plutonium, americium and curium must be classed with uranium and not actinium.

Self-diffusion of ions in solution

A radioactive tracer method has been developed by K. Saddington and J. S. Anderson(1) for measuring diffusion rates of ions in solution, in the absence of any concentration gradients. The method is particularly suited for studying condensation processes in solution, such as the formation of poly-acid anions, e.g.

$$6\,WO_4^{2-} + 7H^+ \rightleftharpoons [HW_6O_{21}]^{5-} + 3H_2O.$$

The technique could well be used in a variety of other types of problems where it is required either to measure ionic weights of dissolved species, or to study transport processes. It has been applied by these workers in a study of equilibria in tungstate solutions, and to follow the intermediate stages in the precipitation of hydrated UO_3 from solutions of uranyl salts (poly-cation formation).

Experiments with the Hahn emanation technique

In the last experiment, which is typical of tracer experiments, the principle employed is to use radioactive atoms that are isotopic with the atoms under investigation to trace the movements of the latter. It is, however, possible to use radioactive elements for other purposes too, when they can be obtained in gaseous form. If a chemical compound could be impregnated with a radioactive gas, it would be possible to investigate the molecular state of the compound, its inner surfaces, or the changes in its structure consequent upon molecular and chemical conversions, etc. This principle was first realized in practice by Professor Hahn of Göttingen (the discoverer of nuclear fission) by taking advantage of the fact that one of the products of the radioactive decay of radium is an inert gas, itself radioactive, called radon; thorium too produces a similar gas, thoron. Radium, or more usually its isotope thorium X, is incorporated uniformly in some solid material by, for instance, co-precipitation. The decay of the radium, or thorium X, results in the formation, uniformly through the material, of atoms of the radioactive emanation (as it is called) radon or thoron. These atoms can escape from the solid by two means only: if they are formed close enough to the free surface they may be shot out by recoil at the instant of creation; if they are deeper in the body of the material they can diffuse out during their lifetime. The ratio of the number of atoms of emanation escaping from the substance to the

(1) See Appendix C.

total number formed, in unit time, is called the emanating power. The emanating power due to recoil depends only on the size of the particles of the substance; the diffusion emanating power, on the other hand, depends on the particle size (which affects the mean diffusion path) and also on the diffusion coefficient of an emanation atom in the crystal lattice. Only the latter term is reversibly dependent on temperature. Processes which change particle size, such as phase transformations, re-crystallization, chemical reaction, etc., produce irreversible changes in emanating power. So alterations in the structure of substances are determined by measuring the changes in the amount of emanation escaping; this is done by collecting the emanation in a suitable electroscope, which measures the charge of the radioactive emanation and hence the number of atoms present. This technique has been considerably developed at Harwell by J. N. Gregory and is a powerful tool for studying processes in solids.

Barium soaps, containing radium or its isotopes, have for some time been known as solids of high emanating power. It has been found that this is a consequence not of excessively small particle size but of the very high diffusion rate of thoron through the crystal lattice. From measurements at low temperatures (down to – 100° C.) the diffusion process has been studied in a series of fatty acid soaps. To study the matter further, Langmuir-Blodgett multilayers have been built up, the first layer of barium stearate being "indexed" with ThX, and variable numbers of layers of inactive barium stearate being deposited on top. The variation of emanating power with numbers of layers, and with temperature, in such a system is capable of fairly exact treatment.

In oxide systems, which have been studied by other workers, the connexion between diffusion of emanation and self-diffusion processes is shown by the marked increase in emanating power, with a high activation energy, observed above the "Tammann point" (= 0.5 × absolute melting-point). Under conditions where the theory of solids leads to the conclusion that the equilibrium of lattice defects should be shifted by changes in the partial pressure of oxygen, it has been found that the diffusion of emanation is also reversibly affected by changes in the gaseous atmosphere from oxidizing to reducing conditions.

New radioisotopes produced by nuclear photodisintegration

As we have seen in Chapter 4, the absorption by a nucleus of a γ quantum of sufficiently high energy can cause disintegration of the nucleus, and the consequent production of a new residual nucleus. This type of reaction has been used by F. D. S. Butement to prepare a number of new radioisotopes of medium and high atomic number, which could not readily be made by other means. Samples of suitable elements were exposed to the beam of γ-rays (maximum energy 23 MeV) from the synchrotron, which causes the ejection from some of the nuclei of either a neutron or a proton. Loss of a neutron produces an isotope of the element irradiated, and loss of a proton an isotope of the element whose atomic number is one unit less than that of the element irradiated. Radioisotopes produced were identified by a chemical separation, and their half-lives determined. Irradiation of an element which is a mixture of several stable isotopes

may produce several new radioactive isotopes, so that it is not always possible, by this means alone, to determine without ambiguity the mass number of new radioisotopes. The following new isotopes were found:

ELEMENT	HALF-LIFE	MASS NUMBER
Arsenic	9 minutes	79
Samarium	8 minutes	143 or 146
Europium	15 hours	150
Lutecium	22 minutes	178 or 179
Tantalum	116 hours	183
Tantalum	48 minutes	185
Rhenium	17 minutes	189 or 191
Iridium	66 minutes	195 or 197
Gold	27 minutes	201 or 203

Radiation chemistry

Radiation chemistry is the study of the effects of radiation on chemical reactions between substances which are generally (though not necessarily) not radioactive. Radiation chemistry is in fact a branch of chemical kinetics, inasmuch as it is concerned especially with changes in the rates at which reactions proceed under irradiation. By no means a new science (the effects of light and x-rays have long been a fruitful field of study), radiation chemistry has acquired a new technological importance, in addition to its interest for fundamental chemistry, because of the many processes in atomic energy projects which take place under intense irradiation of all kinds.

The radiation chemist is interested in the effects of irradiation by heavy particles, protons, α particles, and neutrons, as well as by light particles like electrons and γ-ray photons. The effect of the passage of any of these radiations through a chemical system (e.g. a salt in solution) is generally to increase the chemical activity of the system, that is, the readiness with which the constituents of the system react with one another. The radiations do this by ionizing the atoms or molecules, or by exciting them to higher energy states. Ionized atoms are more active because they have an electric charge which they want to neutralize; excited atoms are more active because they have a surplus of energy which they want to get rid of. The mechanisms by which the different radiations produce these ionized and excited states are various and complicated and there is not space to describe them in detail here. It should be noted, however, that they are atomic rather than nuclear mechanisms; only in certain neutron or proton irradiations are radioactive nuclei formed, and interest is focused not upon this radioactivity, which is purely incidental, but on the atomic ionization and excitation produced by the movement of the radioactive nucleus. Activity to the radiation chemist means chemical activity, not radioactivity, and he is not primarily interested in the nuclear effects produced by radiation. In this he differs from the radio-chemist, whose work we have discussed earlier in this chapter.

The radiation chemistry research at Harwell is split into two sections. In the first the effects of light particles (β particles and γ quanta) are being studied; in

the second, the effects of the radiations from a pile, i.e. neutrons and γ-rays. One source of light particles is the 2-MV Van de Graaff machine, accelerating electrons, which are either used directly or caused to strike a heavy metal target to release γ-rays; a 200-keV x-ray machine is also available. A vessel containing a quantity of the substance to be irradiated is placed close against the window of the machine so that the maximum intensity of radiation is received, and the irradiation is often continued for many hours. The sample is then analysed by the ordinary procedures of chemical analysis to determine what substances are in it, and in what quantities. From these results the nature and rate of the reaction may be deduced. A similar procedure is followed for pile irradiations except that the source is Bepo instead of the Van de Graaff machine, and the sample is placed inside the pile, in a suitable container. Much of the work being done is for the pile programmes and cannot be discussed here, but certain fundamental investigations are of general interest.

One of these investigations is concerned with the radiation chemistry of water and aqueous solutions. Although apparently a simple substance, the behaviour of water in chemical reactions is often extremely complex, and this is especially true of its behaviour under irradiation. This is because the reactions that occur can go either in a forward or in a reverse direction, and the direction favoured changes very readily with quite small changes in the conditions of the experiment. The water molecules tend to decompose into hydrogen atoms and hydroxyl radicals which reduce or oxidize, respectively, other solutes in the system. However, not only is this reaction reversible but other reactions are possible. C. B. Amphlett(1), using dilute aqueous solutions of ferrous sulphate in sulphuric acid, has found that it is possible to obtain complete oxidation of some ferrous solutions and also complete reduction of suitable ferric solutions, and that by varying the conditions the final ratio of the concentrations of the two ions can be made to vary widely. Amphlett obtained these results in systems containing organic complexing agents and showed that oxidation was obtained in systems where the complexes formed by these agents stabilized the ferric ion (e.g. thiocyanate ion), whereas complete reduction was observed in systems stabilizing the ferrous ion (e.g. iron-dipyridyl and iron ortho-phenanthroline). The complexes formed with anions of certain mineral acids may also affect the behaviour under irradiation of ferrous and ferric ions. An investigation of this aspect of the problem is in progress.

The work with pile radiations is directed largely to the solution of technical problems arising in connection with the construction of piles. Such questions arise as: are reactions between graphite and gases like carbon dioxide accelerated, retarded, or not affected by pile radiations? Is the oxidation and corrosion of metals affected by radiation? The answers to these questions will be of fundamental, as well as technical, interest, for these are among the classical reactions of chemistry. Another group of experiments not primarily of technical interest is concerned with the effects of pile radiations on organic substances. It seems probable that atoms, or radicals, may be knocked out of structures like the

(1) See Appendix C.

benzene ring and be replaced by other atoms or radicals, or it is possible that the benzene ring itself may split apart and reform in a different configuration, with consequent changes in the properties and nature of the substances concerned. The ultimate consequences of such changes cannot yet be foreseen, but work has begun to elucidate the processes involved. J. Wright has identified benzaldehyde and phenol among irradiation products from mandelic acid. He has also found that catechol and an aliphatic dialdehyde are produced, in considerable quantities, when solid benzoic acid is irradiated in air. Benzene-water solutions on irradiation have been found to contain phenol, dihydroxybenzenes, and an aliphatic dialdehyde, but diphenyl did not appear in appreciable amounts.

The long-term significance of such fundamental studies is that they may reveal the possibility of preparing certain chemicals which are difficult to obtain by normal synthetic means. Such an outcome would provide ways of utilizing the enormous energy of the radiations from fission products and the stray radiations in pile shields.

Analytical chemistry

The chemical processes associated with the atomic energy programme have brought forward many problems in analytical chemistry. Some of these were related to the need for determining elements which had not hitherto been met in practice, some arose from the radioactive nature of the processes involved, some from the extreme degree of sensitivity demanded in certain analyses. New methods of analysis have become practicable as a consequence of the appearance of strong sources of radiation. An immense amount of work has therefore been done by analytical chemists and some of it has been of a nature that can fairly be called fundamental. We shall glance for a moment at some of the fundamental pieces of work done by the Analytical Group of the Chemistry Division at Harwell.

The analytical chemistry of the heavy elements has of course been of particular importance in view of the nuclear engineer's concern with elements like uranium and plutonium. In determining uranium it has been necessary to develop more and more sensitive methods so that the smallest traces, for example in the urine of workers handling the metal, can be measured accurately. To this end such physico-chemical methods as fluorophotometry, spectrophotometry and polarography have been greatly refined and extended. Plutonium, being an entirely new metal, has presented some interesting problems, many of which arise from ignorance of the fundamental chemistry of the element. At present the valence states of plutonium are being studied using organic reagents as complex formers.

Mention has been made of the polarographic method of analysis. This technique depends on the fact that under certain conditions, when a steadily increasing voltage is applied between electrodes in a solution containing certain substances, the resultant current through the solution varies in a manner that is characteristic of the substance concerned; moreover, the magnitude of the variation gives a measure of the concentration of the substance. Thus by a comparatively simple procedure it is possible both to identify the elements and to determine the amount

present. Moreover, the method is very sensitive and requires only a small sample. In its standard form, however, it is less satisfactory when the concentrations of the elements are widely different, which is a situation that often faces the analyst in an atomic energy project.

At Harwell, major advances have been made in the technique of polarography. Smales and Airey have developed a double electrode apparatus which has led to an increase in the sensitivity of the method (i.e. its ability to distinguish small concentrations) as well as its selectivity (i.e. its ability to distinguish between different elements). Barker has applied new electronic techniques to polarography and very greatly increased its sensitivity—to such an extent that the residual impurities in distilled water show up clearly in the polarograph diagrams.

Radiochemical methods have been used to increase the sensitivity and accuracy of analytical procedures, in certain instances. For example, it was necessary to know the concentration of strontium in sea-water in order to establish the maximum amounts of radioactive strontium which could be allowed to escape into the sea. The quantities involved were very small, of the order of 10 parts of strontium in a million of sea-water, and previous determinations had given results that varied over the range from 8 to 40 parts per million. The discrepancies arise mainly from uncertainty about how much strontium was precipitated at one stage of the process. Smales(1) has worked out a method in which the amount precipitated is measured in two ways, by using radioactive strontium as a tracer and by a spectroscopic method using the flame spectrum. The method is considered to be more reliable than others; the result obtained was 10 parts per million with an overall error of $\pm$ 10 per cent.

An analytical procedure remarkable for its sensitivity is that known as radioactivation analysis. In this method the sample, containing very small amounts of the element to be determined, is irradiated in a neutron flux so that radioactive isotopes of the element to be determined are formed; the amount of these isotopes can be measured by counting the particles which they emit, whence the amount of the element originally present can be determined. The method was first proposed in 1934 but until the advent of the nuclear reactor it was of limited utility. Now it is coming into its own. With the fluxes available at Harwell it is possible, with the most favourable elements, to detect as little as one million millionth of a gram (10^{-12}); this should be compared with the next most sensitive method, emission spectroscopy, with which the least that can be detected is a thousand millionth of a gram (10^{-9}). With larger neutron fluxes the method would be even more sensitive. The radioactivation method is also usually quicker than the spectroscopic; thus the amount of hafnium in a sample of the metal zirconium (of which it is a common contaminant) can be determined in five minutes or so, compared with several hours by the spectroscopic method. The method has been used at Harwell to determine the amount of arsenic in germanium. The lower limit of determination using existing conventional methods is about 1 to 2 parts per million, but using the radioactivation method it is possible to determine as little as one-tenth of this. The result is of interest to the electronics industry

(1) See Appendix C.

because of the importance of germanium in the modern transistor, or crystal valve. It is believed that the failure of some samples of germanium to have the required electronic properties arises from the presence of impurities. The recent Harwell experiments have shown that, if this is so, arsenic is by no means the most important of them.

The "hot" laboratory

Several references have been made in this chapter and elsewhere to the precautions that have to be taken when experimenting with radioactive substances. If the quantities of active material are kept extremely small, as in tracer experiments and microchemistry, and the less dangerous isotopes are used, the work may, with due precautions, be done in ordinary chemical laboratories. But as soon as the level of activity exceeds a very low value, it becomes essential to build special laboratories designed to reduce to a minimum the chance that a worker will come into contact with active material. Such buildings are generally called hot laboratories, the adjective referring to high radioactivity.

The hot laboratory at Harwell is the only one of its kind in Europe, and when it was completed in the summer of 1949 it was the most up-to-date in the world. It is a long, two-story building which presents an unusual appearance by reason of the complete absence of windows in the upper story. The reason for this is that there are no laboratories or offices in the upper floor, but the whole space is occupied by ventilating equipment. In plan the building forms a rectangle with a central courtyard. The front block of the rectangle contains the main entrance and offices, stores, workshops, and a few non-active laboratories. At each end of this block is a group of changing rooms connecting it to the L-shaped wings of the building. The short arms of these L's form part of the back block of the rectangle; the back block is completed by the plant room, which separates the short arms of the L's and projects forward into the courtyard. This plant room is considerably higher than the rest of the building and contains the ventilating machinery, control equipment and exhaust stack.

The L-shaped wings contain the hot laboratories themselves. Some of these (those in the long arms of the L's) are arranged in suites of three rooms, office, laboratory, and vestibule; in the latter there is a contamination monitor, so that workers can check their hands and feet and clothes, and a wash-basin and air drier fitted with foot controls, so that active material can be washed off without contaminating the washing equipment. Similarly doors in the corridors of the hot wings are opened automatically, by photoelectric cells, so that they need not be touched by contaminated gloves. The laboratories themselves are fitted with fume cupboards of special design, as well as more orthodox benches, and with lead-lined cabinets for storing radioactive material. Services like gas, hot and cold water, rough vacuum and the like are laid on to each bench and fume cupboard, the pipes and ducts being marked with a distinctive colour characteristic of the service involved; this colour coding is used throughout the building. The laboratories in the short arms of the L's, in which the most active materials are used, are arranged rather differently. In one of them there is a number of

closed compartments, fronted with Perspex, in which apparatus is manipulated by remote control; these are for work with considerable quantities of α active material uncontaminated with γ activity. Once an experiment has begun, these compartments may be entered only when clothed in a protective suit, not unlike the rubber overalls of naval frogmen, and a helmet and respirator.

Because the most serious hazard arises from radioactive dust, very stringent precautions are taken to prevent its formation and to remove it if it is formed. All the active laboratories are fitted with double, hermetically-sealed, glass windows, the insides of which present a single plane surface flush with the wall; angles between walls, floor and ceiling are rounded; lighting fittings are recessed behind flush glass panels; a "hospital finish" is used on all surfaces. The covering of the walls is a special paint which, in the event of contamination, could be stripped as a single sheet.

To remove dust the laboratories and the fume cupboards in them are connected to the elaborate ventilating and air-conditioning plant. By this means the air can be changed as often as 120 times a minute throughout the building, though ordinarily a rate of 40 times a minute suffices. Any solid radioactive material swept out by this system is removed from the air stream by highly efficient precipitators; the air is then exhausted through the stack in the tower. Radiation monitors are fitted in all laboratories and adjacent to fume cupboards and storage cabinets; these provide local indications of activity levels. The activity of the ventilating air from each laboratory and in the exhaust stack is also monitored and warning given if it exceeds a specified level. All the ventilation is controlled from a control-room in which indications are given of rates of flow and activity throughout the building.

The short arm of the other L is built of concrete, and is without windows. Experiments with large amounts of γ activity, such as the dissolving of an irradiated uranium slug from the pile, are carried on here.

METALLURGY RESEARCH

It has been made clear in other chapters of this account that many of the most urgent of our unsolved problems lie in the field of metallurgy. These are of course being investigated primarily because of their importance to various reactor applications, but several of the researches are of fundamental interest in metal physics, some for the light they throw on the properties of metals in general, others because they are concerned with metals which hitherto have seldom been studied. Among the experiments in the latter category are those concerned with uranium.

Properties of uranium crystals

Uranium is of considerable interest to the metal physicist because of its unusual crystal structure. Most metal crystals are built up either of cubic units or of hexagonal ones like a honeycomb, but "orthorhombic" uranium, the type existing at room temperature, is built up of unit blocks with their three edges all of different lengths. The characteristics of the deformation under stress of cubic and hexa-

gonal metals are fairly well known. They deform either by slip or "twinning" on one or two particular planes of atoms at room temperature. In slip, thick sheets of atoms glide over each other on these planes by variable amounts; in twinning the gliding sheets are only one atom thick and each sheet glides on a particular plane by exactly the same amount relative to its neighbour, a number of sheets gliding simultaneously to form a "twin".

R. W. Cahn at Harwell has found two planes on which slip occurs in uranium, but the main process by which this metal deforms on first stressing is twinning, and twins on three different families of planes have been observed. As deformation proceeds, the slip mechanism becomes progressively more important. The crystallographic details of the twins in uranium are, of course, different from those in cubic or hexagonal metals; for one thing, two entirely different types of twins have been found to occur (called shears of the first and second order).

The temperature dependence of twinning in uranium is now being examined by making use of the fact that each time a twin is formed a faint but audible click or "cry" is emitted. Twins in uranium are formed by heating or cooling a piece of metal because the individual crystals expand or contract by different amounts in different directions and so distort each other. These clicks are picked up by microphone, amplified and recorded.

Cahn has also made large single crystals of uranium by extending bars of strain-free metal by a small critical amount and then heating these very slowly. These crystals are at present being used to study twinning, and will also be used to measure other properties such as the electrical conductivity which depend on direction inside the crystal. Single crystals of other metals (including beryllium) are also being made for similar purposes.

Uranium alloys

It may be possible to make better fissile fuel elements by alloying uranium with other metals, but unless we understand how and why these alloys are formed, and how and why the properties of uranium are consequently affected, development of a suitable alloy for a particular purpose will remain a laborious and uncertain art.

An alloy is made by melting a mixture of two or more metals and its properties depend on the proportions present and on the type of alloy that is produced. Usually the alloying element either goes into solution in the parent metal or forms an intermetallic compound with it, or does both. In a solid solution, atoms of one metal either replace atoms of the solvent metal more or less evenly in the crystal lattice positions (substitutional solid solutions), or the solute atoms are distributed in the interstices of the solvent lattice (interstitial solution). The relative size of each type of atom is thus an important factor governing solid solution formation. When an intermetallic compound is formed, the two metals are present in fixed positions relative to each other in a new crystal lattice; the type of compound formed depends on other properties of the atoms in addition to size, such as the number of valency electrons surrounding them and the electrochemical attraction between them. A group under B. W. Mott is studying,

initially, binary alloy systems which test systematically the way all these factors operate in forming alloys with uranium.

After melting, alloys of selected compositions throughout each system are held at fixed temperatures until they have reached an equilibrium state and then quenched to retain evidence of their structure. These alloys are then examined, principally by x-ray diffraction methods or under a microscope. For convenience a diagram can be constructed showing the structures of all alloys at temperatures up to their melting-point, the extents of solid solution, and the ranges of composition in which the various compounds occur.

Hume-Rothery([1]), Raynor and others have found that in simpler metals such as copper, silver and gold, and to a lesser degree in aluminium and magnesium, the forms of these phase diagrams are governed by rules of alloying behaviour which depend on such factors as the atomic size and the valency electrons contributed by the metals involved. The research on uranium alloys is showing that similar relations hold for these alloys, but the more complex distribution of electrons in the uranium atom appears to allow it to act with several different valencies. For instance, from the behaviour of uranium-molybdenum alloys it would appear that the "orthorhombic" uranium, stable at room temperature, may be acting as though it had four valency electrons, while the "body centred cubic" form of uranium which exists just below the melting-point may be effectively six valent. Experiments on alloys with niobium and zirconium, which have atomic sizes similar to molybdenum but different valencies, will test these conclusions further.

It has been found that several series of compounds occur in alloys containing the very similar metals, manganese, iron, cobalt and nickel. These particular compounds owe their formation principally to a good fit or geometric packing of the atoms, modified slightly by such factors as the average number of valency electrons per atom (electron: atom ratio). For example, the compounds UMn_2, UFe_2, UCo_2 and UNi_2 can exist because the ratio of the atomic sizes in each case is suitable for ideal packing, but the particular crystal structure each assumes can be explained in terms of the electron: atom ratios.

As information of this kind becomes more complete it will be possible to predict, with more certainty than at present, the form of a given alloy system of uranium, and ultimately of other heavy elements such as thorium, and to choose alloying additions which will produce particular properties of technological importance.

The examination of metals under polarized light

The structure of an ordinary piece of pure metal is complicated. Usually it is polycrystalline, that is, it consists of a large number of small crystals of the metal oriented at random with respect to each other. The crystals may be as small as 0.0001″. Sometimes the orientation is not random, but a large number, perhaps the majority, of the little crystallites lie with their axes in the same direction.

([1]) W. Hume-Rothery—" The Structure of Metals and Alloys".

Sometimes the metal contains a high proportion of large crystals, and with special treatment the whole piece may be made into a single crystal, several inches long. The properties of the piece of metal will vary greatly according to its microstructure, i.e. size, microscopic distribution and relative orientation of the individual grains. One way of studying the structure of a metal is to examine a prepared flat surface under a microscope to discover visually the arrangement of the grains. Usually the surface is etched with a reagent chosen to suit the metal, so as to bring out the separate grains. This technique is more difficult to apply to uranium than to other more common metals, but it has nevertheless been applied successfully.

In the normal way the light used for the examination of metal surfaces under the microscope is "vibrating" in all directions, but it is possible to restrict the vibrations to one plane by the use of a polarizing unit; light so restricted is said to be polarized. When polarized light is reflected from a metal which has the same properties in all directions, i.e. one which has a cubic crystal structure, the nature of the polarized light is unaffected by reflection and the light can be completely extinguished by passing a reflected beam through a second polarizing unit placed at right angles to the first unit. With non-cubic metals, however, the mode of reflection of the beam depends on the orientation of the grains on which it is incident and the amount of light transmitted by the second polarizing unit when in the "cross position" also depends on the orientation. Thus in a polycrystalline specimen, if suitably prepared, each grain will be characterized by a particular reflected intensity and the grain distribution can be studied by this means as an alternative to etching to reveal the grains. By the insertion of a quartz plate in the optical train the grains can be made to appear variously coloured, the colour of any particular grain depending on its orientation. By suitably etching cubic metals similar results can be obtained to those which are produced on polished surfaces of non-cubic metals. B. W. Mott has examined a number of metals in this way, including aluminium, beryllium, bismuth, cadmium, magnesium, tin and zinc, and a number of alloys.

Powder metallurgy

There are many methods by which metals can be fabricated into shapes like sheets, rods, tubes, and so forth, and in these forms they are used for constructional and other purposes. For example, metals can be cast, rolled, extruded, forged or machined, but one of the less familiar techniques is fabrication from powder. If a fine powder of a metal, say beryllium, is placed in a mould and subjected to a pressure of many tons to the square inch, and then heated to an elevated temperature, a dense, fine-grained, and usually very uniform piece of metal is obtained which, insofar as its physical properties are concerned, may be superior to metals prepared by other processes. This technique, known as powder metallurgy, offers particularly attractive possibilities when applied to metals of interest in atomic energy work, e.g. beryllium, zirconium and niobium (columbium). A group working under the general direction of A. Blainey at Harwell has therefore undertaken a study of the fundamentals of this process.

Blainey's group has examined the sintering of metal powders at temperatures up to 1200° C. in a vacuum (pressure 2×10^{-6} mm. of mercury) and hot compacting at temperatures up to 1000° C. under a pressure of 15 tons/sq. in. One important feature of these processes is the influence of the atmosphere in which pressing or sintering is done. For example, it has been found by J. Williams that if a ductile metal powder is pressed at, say, 40 tons/sq. in. in air, air at pressure up to 15 tons/sq. in. can be trapped between the particles. On subsequent sintering the trapped air may react with the surface of the particles and affect the rate at which sintering proceeds.

As a result of these and other investigations some improved methods of fabrication by the technique of powder metallurgy have been developed. For instance, metal tubes and sheet (e.g. beryllium x-ray windows) have been fabricated direct from powder, and without further processing. Another application is the manufacture of metal compacts impregnated with plastic of low friction coefficient for use in bearings.

The effect of irradiation on metals

We have referred in a number of places to the need for discovering the effect of intense neutron and γ radiation on the properties of metals which might be used in piles. Among the investigations of this kind which are being made by the Metallurgy Division is the study by E. R. W. Jones of the effect of irradiation upon the mechanical properties of metals and alloys, particularly their elasticity and creep.

In these experiments a test specimen is subjected to stress by, for example, hanging a weight on it. The resultant strain, that is the ratio of the change in length (or in radius) to the original length (or radius), has to be measured with an accuracy about 1 part in 100,000.

The experiments are made either whilst the specimen is still being irradiated or after the irradiation has been completed. In this way the permanent effects of the radiation may be separated from those that are transient. The first type of experiment has to be performed in a small space inside the pile, and the methods for applying the stress and measuring the strain must be such that they can be controlled from a distance and will not be affected by the radiations. As an example of this type may be quoted an experiment on the creep of aluminium tubes. In this the stress is applied by means of compressed air inside the tube. The resultant change in the diameter of the tube is determined by measuring the change produced by the stress in the pressure drop of air flowing through the annulus formed by the tube under test and a larger, unstressed tube surrounding it.

Research on ceramics

The metallurgist requires refractory ceramics, for example to make crucibles capable of withstanding the very high temperatures required for experiments on uranium and other metals. Both Metallurgy and Chemical Engineering

Divisions have an interest in this field, the latter being particularly concerned with beryllia, which requires special laboratory facilities on account of the physiological hazards involved, and with technological problems generally. In the Metallurgy Division, the ceramics group under P. Murray has done fundamental research on slip casting, phase transformations in ceramics, and the mechanism of sintering, in the course of its work on the development of techniques for the fabrication of high-temperature materials such as oxides (other than beryllia), carbides and sulphides.

A well-established method of making ceramic articles is that known as slip casting. The slip is a paste of the powdered material with water; it is poured into a plaster-of-Paris mould, which absorbs the water, leaving a dry, hard article of the desired shape. The slip-casting of pure oxides has been investigated by Murray's team and the effect of pH (hydrogen-ion concentration, a measure of acidity and alkalinity) on the viscosity and sedimentation volume of the slip has been studied in detail. With certain ceramic oxides, of which alumina is an example, the curves connecting pH with viscosity and pH with sedimentation volume have been found to have sharp minima (e.g. at pH 3.5 for alumina). An explanation of this effect has been found, based on the fact that the hydroxide can function either as an acid or as an alkali and on the assumption that the solid particles of the slip can adsorb either the metallic or acidic type of ion, depending on the pH. The relation between pH and viscosity is of practical importance because, by altering the pH, the viscosity of the slip can be adjusted to meet any requirement. The limitations to this possibility have been explored and it has been found that, in general, pH values on the acid side of the minimum are most satisfactory.

Another very useful material for high-temperature work is zirconia, but unfortunately this is extremely difficult, if not impossible, to fabricate. The reason for this difficulty is that a reversible phase change in the structure of the material, from monoclinic to tetragonal, occurs at 1150° C. on heating, so that when the material cools there is a volume expansion at this temperature which shatters the article. The kinetics of this phase change have been investigated, using an accurate method of measuring specific gravities, and it has been shown that the results are consistent with the hypothesis that the shattering occurs as a consequence of growth of one phase from a nucleus in the other. The possibility of stabilizing the high-temperature (tetragonal) modification by additions of lime and magnesia has been investigated, especially with regard to the effect of stabilization on the resistance to thermal shock of the fired compacts. It has been found that partly stabilized bodies are by far the most resistant to thermal shock and that this observation can be correlated directly with thermal expansion. Both the unstabilized and the completely stabilized zirconia have greater thermal expansion than the partly stabilized bodies because in the latter the residual inversion results in a contraction in volume, on heating, which reduces the thermal expansion.

An interesting parallel with powder metallurgy is the fabrication of ceramic shapes by hot pressing in graphite dies, and technical advances have been made in the application of this method, which has several advantages over the more

common slip-casting and cold-pressing methods. In the first place, it is a single-stage operation, since there is no need for sintering. Secondly, it is easy to make shapes which are completely free from pores, a difficult thing to achieve with cold-pressing and sintering. Moreover this very desirable freedom from pores can be obtained at temperatures very much lower than those needed for sintering after cold-pressing, with the result that there is no excessive growth of crystals in the shape. Crystal growth has a deleterious effect on the properties of the final article, and is difficult to avoid by application of the ordinary techniques. Finally, shapes can be made to closer tolerances than is possible by other methods. This hot-pressing method has been applied successfully to a variety of materials the fusion temperature of which has ranged from 900° to 3000° C. With some oxides difficulty has been experienced because of formation of carbide by reaction with the graphite crucible, but even then good results could be obtained by hot-pressing at temperatures below the critical temperature of carbide formation.

NINE

EXTRAMURAL RELATIONS

ALTHOUGH Harwell has grown in five years to have a considerable staff and extensive experimental facilities, the success of atomic energy research and development in this country will inevitably continue to depend to a large extent on the good will and help of great numbers of people outside the Establishment. On the other hand, it can be confidently expected that Harwell staff will contribute to the common pool of knowledge in many ways.

Of the wide variety of contacts which make up Harwell's extramural relations, this account will mention briefly those that fall into two important categories: collaboration through research and development contracts that have been placed with academic, industrial or Government laboratories; and the equally important, though usually less formal, contacts which have as their chief object the exchange of scientific and technological ideas and information.

Extramural research and development contracts

The pressure on Harwell staff makes it essential to enlist the aid of industrial and other laboratories on many problems, and thus to enable Harwell staff to concentrate on work to which their facilities are specially suited. As Harwell has grown and the scope of this programme has widened, the need for extramural help has not diminished, but on the contrary has grown steadily, so that the number of research and development contracts, and the work carried out under them, is now many times greater than when Harwell was started. The arrangements for work to be done under this type of contract are made by the Extramural Research Division of the Establishment, and the programme is settled in close consultation between members of this and other divisions at Harwell and the outside organization concerned.

Many of the problems tackled extramurally are those to which industrial organizations, university laboratories, or other Government research departments can apply their existing experience. This has been of particular benefit in developing production methods, either on a pilot plant or full plant scale, for new materials essential to the atomic energy research programme. For instance, the initial development of uranium metal extraction and fabrication, and the manufacture of the pure graphite used as a moderator in the Harwell piles, were done outside Harwell, largely by industry. Existing industrial experience is also drawn upon to help solve a wide variety of technological problems in the fields of metallurgy, engineering and chemistry. In many such cases the special needs of atomic energy led to modification of previous practice, in establishing which the association of the various groups of scientists, engineers and technicians, industrial and Governmental, proved of great benefit.

Electronic equipment has been very successfully developed in the same way. Prototypes of many different kinds of instruments have been made at Harwell, and they have then been developed by industrial firms to the production stage. Such instruments are then usually available in considerable numbers, not only to the Atomic Energy project but also for universities and other users in this country and for export. The needs of these other users are frequently considered at a very early stage of the design and incorporated where possible.

In the field of large electrical machines, extramural research and development contracts have been used almost exclusively. The cyclotron, the synchrotron, the Van de Graaff machines and the electromagnetic separators were all made by industrial firms working in close co-operation with Harwell staff and to Harwell requirements. Some of these machines have been the forerunners of similar ones for other use.

It is natural that university laboratories have generally been reluctant since the war to take on applied research contracts, since their first preoccupation is with teaching and fundamental research. Nevertheless, the number of Harwell contracts with universities is now steadily on the increase again, and, apart from these agreements, there are many successful informal contacts. Work is going on in many laboratories in physics, chemistry, metallurgy and engineering which has considerable bearing on the Establishment's own problems, and visits by individuals, colloquia and conferences are held where they are likely to be of mutual benefit.

Exchange of information

It is, of course, extremely important that the internal organization of a research establishment should be such as to foster research initiative and interchange of ideas between members of the staff. Every effort to this end is made at Harwell, through station lectures, colloquia, information services and individual contacts. But this is not considered sufficient, even with a staff of hundreds of scientists working in a dozen overlapping fields of science. The initial period of enthusiasm, which almost invariably exists in an organization whose members are brought together with fresh minds from many different places, may too easily be succeeded by staleness if there are not frequent contacts with outside scientists who are working on similar problems. The problem is not new, and the means to overcome it are well known, but it cannot be stressed too much that the extent to which it is solved determines to a considerable extent the ability of a research organization to continue at its highest rate of progress. So at Harwell outside connections are fostered through conferences and through individual contacts, with both universities and industry. The first nuclear physics conference held at Harwell was in 1947; another more ambitious nuclear physics conference was arranged in Oxford in September, 1950. A chemical conference, arranged jointly by the Chemical Society and the Atomic Energy Research Establishment, was held at Oxford in 1949. A small conference in cosmic rays was arranged by the Establishment in March, 1950. An international conference on isotopes techniques was held in Oxford in July, 1951. There have also

been a number of smaller conferences with United States and Canadian scientists under the programme of technical co-operation between the three countries. Members of Harwell staff have attended and read papers at many international conferences.

Individual contacts are widespread and exceedingly important: the Establishment enjoys the help of many consultants from universities and from industry, and a number of Harwell Associates have been appointed to foster less formal contacts with scientists whose work and interests are allied to its own. There have been many talks from distinguished scientists who have visited Harwell from time to time. A limited number of Harwell Fellowships is offered annually to research workers of promise, to work at Harwell for periods of about two years. Members of Harwell staff, on the other hand, visit universities for discussion and in some cases for periods of special training.

There is a converse to most of what has been said in the preceding paragraphs; it is conceived to be an obligation of the Establishment to pass on to science and industry in this country those fruits of its work which are not restricted by security considerations. This part of its activities has only just begun, but it will be developed as opportunity offers. For example, one of the present limitations on the use of isotopes in industry (discussed in Chapter 4) is the lack of research workers who are familiar with the special techniques which have to be employed. While it is the primary responsibility of universities to train research workers, it has been found necessary for a limited amount of training to be given at Harwell—at least for the next few years—if industry is not to lose time in making full use of this powerful new research technique. This training is provided in the courses at the Isotope School, to which reference was made earlier.

Accounts of non-secret work at Harwell are published in the usual way in scientific and technical journals and some 250 papers have been accepted so far; papers are read by members of the Establishment to learned societies and at special courses of lectures arranged from time to time by universities; and research workers from universities and elsewhere are frequent visitors to the Establishment. To supplement the publications in the scientific press arrangements have been made for the sale, through H.M. Stationery Office, of suitable A.E.R.E. reports on unclassified subjects. But more may have to be done, particularly through such organizations as the industrial Research Associations, and through the research and development establishments of other Government Departments, to ensure the widest knowledge and use of valuable results, techniques and experience gained at Harwell, which may have application to subjects outside atomic energy.

APPENDIX A

SENIOR STAFF OF THE ATOMIC ENERGY RESEARCH ESTABLISHMENT

DIRECTOR: SIR JOHN D. COCKCROFT, F.R.S.

SECRETARY: MR. R. G. ELKINGTON (until Nov., 1951)
MR. D. R. WILLSON (from Nov., 1951)

HEADS OF DIVISIONS

Chemical Engineering	Mr. A. S. White
Chemistry	Dr. R. Spence
Electronics	Dr. D. Taylor
Engineering	Mr. H. Tongue
Extramural Research	Mr. D. R. Willson
General Physics	Mr. D. W. Fry
Health Physics	Dr. W. G. Marley
Isotopes	Dr. H. Seligman
Medical	Dr. Katharine Williams
Metallurgy	... Dr. H. M. Finniston
Nuclear Physics	Dr. E. Bretscher
Radiochemical Centre	Dr. W. P. Grove
Reactor Physics	Dr. J. V. Dunworth
Scientific Administration	Mr. J. F. Jackson
Theoretical Physics	—

APPENDIX B

THE HARWELL REACTORS

Properties of nuclear reactors

AS a preliminary to detailed descriptions of the two reactors at Harwell, and as a footnote to the remarks on reactors in the body of this account, it is thought that a summary of some of the general properties of reactors may interest some readers.

It will be remembered that in the fission process an atom of uranium 235 is split into two unequal fragments by the impact of a slow neutron and that from this splitting between two and three new neutrons are born. These new neutrons can in their turn cause other fissions, and so, as long as more neutrons are born than die, the reaction will propagate itself, becoming what is called a chain reaction. This is the fundamental principle of the nuclear reactor. There are however certain complications which have to be taken into account.

In the first place the new-born neutrons possess great energy and are consequently moving very fast, with speeds around six thousand miles a second. This does not prevent them from causing further fissions—if it did there would be no atomic bomb—but they are less likely to do so than if they were travelling with much lower speeds around twelve miles a second. Consequently in most reactors the fast neutrons are slowed down by allowing them to make collisions with the atoms of a so-called moderator. Because a neutron will lose more energy in a collision with an atom of mass comparable with its own, moderators are made of light elements such as carbon (in the form of graphite) or heavy hydrogen, in heavy water; ordinary hydrogen cannot be used because a high proportion of neutrons is absorbed by the atoms instead of bouncing off them. Slabs of the same substance as the moderator are also placed round the pile of reacting materials to reflect into it neutrons that would otherwise have gone straight out. But no reflector is perfect, and some neutrons are lost from the surface. The proportion so lost can be reduced by making the pile larger, and there is a "critical size" below which so many are lost that the pile will not work at all. It is for this reason that a natural uranium pile is inevitably a large machine.

Another important property of the neutrons born in fission is that not all are emitted at the instant of fission. A very few (about $\frac{1}{2}$ per cent) arise from radioactive decay of the fission products, and their appearance is delayed several seconds. The consequence of this is that the speed with which the neutron population increases in a pile of just above critical dimensions is considerably reduced, so that the divergence of the reaction occupies a short but finite period of time during which it can be controlled. In designing a reactor this effect is taken into account by means of a constant called the pile period, which is a measure of the time taken for the neutron population to increase (or decrease)

when the equilibrium is disturbed; obviously the pile period will depend on the delayed neutrons, as well as on such things as the lattice dimensions and moderating material, which affect the average lifetime of "prompt" neutrons. The operation of a pile is controlled by moving in and out of it rods of neutron-absorbing material which, by removing more or fewer of the excess neutrons, vary the power level at which the reaction proceeds. An unusual point about the control mechanism is that one does not simply pull the rods out to raise the power and push them in to lower it. The function of the control rods is essentially to keep constant the number of neutrons in the pile, and hence to hold the rate at which the reaction is proceeding at a steady predetermined value; when it is desired to raise the operating power, the rods are withdrawn a little so as to allow the number of neutrons to increase. These extra neutrons then produce more fissions, which in turn produce yet more neutrons, so that the rate of the reaction (and consequently the power level) rises. When the power reaches the desired value the control rods are pushed in again to their original position to absorb the excess neutrons and stabilize the reaction at its new rate. In technical language, the reproduction constant k of the pile is allowed to exceed one until the desired level is reached and then it is stabilized at unity again.

The fission process owes its economic importance, of course, to the fact that it is accompanied by the release of a considerable quantity of energy. This energy, which amounts to about 180 MeV in each fission, manifests itself as heat in the uranium. In low-power reactors the total heat so generated is insufficient to do any harm; in larger reactors it has to be removed if the uranium fuel elements are not to be damaged. But in all those so far built the extraction of heat has been merely a question of getting rid of a waste product. In a reactor designed to produce power, however, heat is the primary product. It will therefore have to be removed economically and at a temperature high enough to allow it to be transformed efficiently into mechanical energy. The discovery of the best means of achieving these ends forms a major problem in developing nuclear reactors for power production.

We have referred to the two unequal fragments into which the uranium atom splits when it undergoes fission. These, the so-called fission products, are isotopes of elements near the middle of the periodic table; they are invariably radioactive, and are formed in the uranium metal. When the metal is treated to extract plutonium from it, enormous quantities of these fission products are extracted at the same time, usually in the form of highly radioactive solutions. The disposal of such dangerous waste products presents the chemical engineer with one of his more formidable problems.

Gleep—the graphite low-energy experimental pile

Gleep is a slow neutron reactor using graphite as a moderator and natural uranium and uranium dioxide as fissile material. It was constructed to meet two main requirements, viz. to run at as high a power as possible without elaborate cooling arrangements and to compare slow neutron absorption cross-sections of the elements by the pile modulation method.

As a later development it was found that Gleep could be used to provide an accurately known and reproducible thermal neutron flux in the range 10^6 to 10^8 n/cm^2/sec. This flux can now be used to determine activation cross-sections.

The pile is built in the form of a right octagonal prism of graphite lying on one of its sides. The reacting core is cylindrical (length 5.24 m., radius 2.86 m.) with the uranium rods lying horizontally in the form of a line lattice of pitch 7¼ in.; the reflector forms the remainder of the octagon, the lower corners of which are filled in with graphite introduced for constructional reasons only.

The total quantity of graphite in the pile is 505 tons. The graphite is stacked in forty layers, each layer being built with graphite blocks stacked in such a manner as to resemble a parquet floor. The graphite blocks are of two standard types each measuring 7¼ in. × 7¼ in. × 29 in. Various non-standard and half-blocks are incorporated, but leading dimensions of all blocks are based upon the fundamental "pitch" unit of 7¼ in. The edges of some blocks are chamfered, and grooves are cut in other blocks, so that a lattice of diamond-shaped holes of 1.85 in. side runs through the pile from A face to C face.

The reacting core is loaded with uranium metal up to a radius of 1.75m., the outer region being loaded with uranium dioxide. The uranium metal is in the form of cylindrical bars 12 in. long by 0.9 in. diameter, and is sprayed with aluminium of 0.003 in. thickness to prevent the escape of recoil fission products. In order to increase its density the uranium dioxide is pressed into pellets 1.60 in. in diameter and 2 in. long. These pellets are wrapped in paper containers and inserted in batches of six into aluminium cans of 0.01 in. thickness. This makes a uranium dioxide cartridge 12 in. long by 1.62 in. diameter, weighing 2.6 kgm. Gleep contains 12 tons of uranium metal and 21 tons of uranium dioxide.

There is a 3 ft. air space between the sides of the graphite structure and the inside of the biological shield. This allows access to the inside of the pile if the necessity arises for the removal of any of the uranium cartridges. The concrete biological shield is of 5 ft. thickness around the sides and is 4 ft. thick on the top of the pile.

On the B face of the pile there is a hole in the shield which is filled by graphite blocks to form a square section thermal column of 5 ft. side and 7ft. long. There is a large access hole on the top of the pile so that an additional thermal column can be stacked on the top of the pile if it is required.

There is an elementary ventilation system for the pile capable of delivering 5,000 cu. ft./min. of air. This is provided to remove active argon from the pile, and to provide some cooling of the uranium cartridges. The air is forced by the baffle on A face to flow over the uranium cartridges and is extracted by a suction fan on the top of the pile. When the air system is on, it is arranged that the pressure inside the pile is always less than atmospheric; this ensures that there is no leak of radioactive air into the building. The air is ejected through a short stack on the roof of the building (the top of the stack is 60 ft. above ground level) and when the air has diffused to ground level outside the building its activity is below the tolerance level.

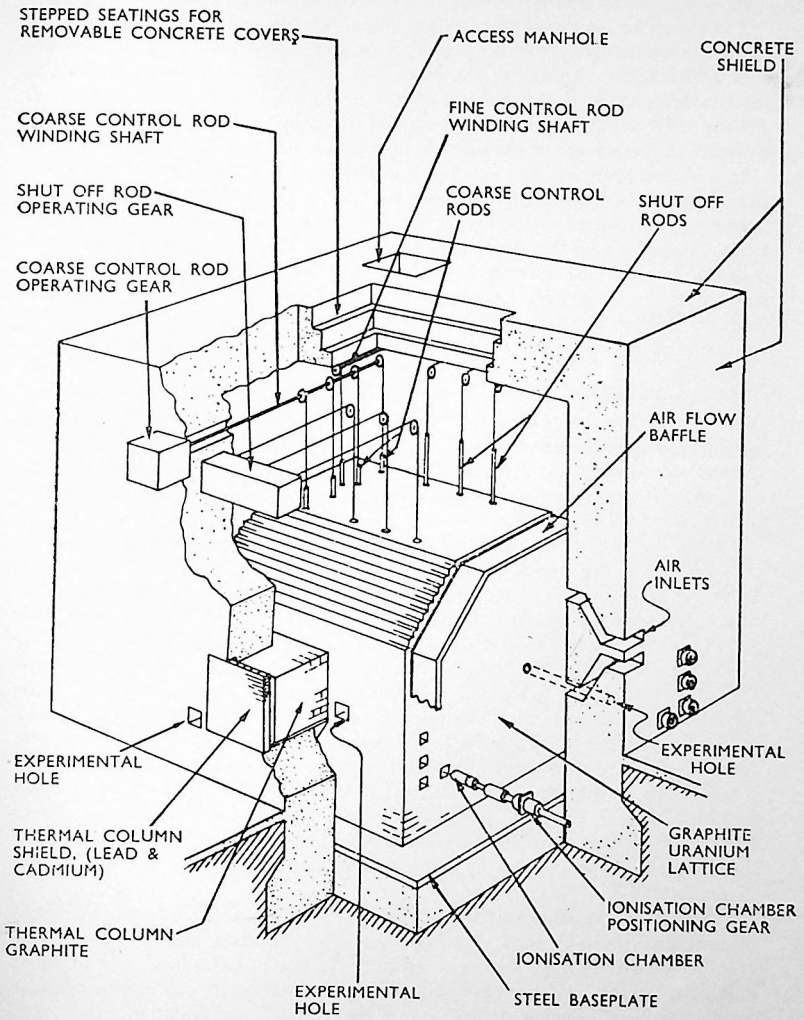


Fig. 8. General arrangement of Gleep.

By using the air-cooling system, the pile can be run at a power of 100 kW.

The Gleep has an excess effective reproduction constant of 2×10^{-3} when all absorbers are removed from the pile. This excess k is controlled by four cadmium rods which move together as shown in Fig. 8. These four rods are known as the coarse control; the single rod shown in Fig. 8 is used as a fine control. All the control rods can be moved up and down by electric motors which are situated on the outside of the pile and operated from the pile control-room.

In addition there are two sets (each consisting of three rods) of emergency shut-down rods. These cadmium rods are held right out of the pile when it is operating, by magnetic clutches. If the pile power rises above a pre-set level, a trip circuit cuts off the current to the magnetic clutches, and the emergency rods fall into the pile under gravity. On the end of a shut-down-rod shaft is a disc keyed to the shaft and positioned to rotate between the poles of four electromagnets to form an electric brake. As the rods approach the "fully in" position, the magnets of the brake are energized, and the rod motion is retarded to a gentle halt.

To indicate the position of the control rods in the pile two transmitter magslips, driven through gearing so that one rotates fifty times as fast as the other, are mounted near the drive motors. These transmitters are electrically connected to receivers in the control-room, so that direct readings of the positions of the rods are given on two dials. By this means the position of the rods can be read with an accuracy of $\pm$ 1 mm.

The power level of the pile is measured by six ionization chambers of 5 litres volume, containing boron-trifluoride gas at a pressure of 20.7 cm. mercury. Three of these chambers are used for pile control, and the other three are used to separate the emergency shut-down mechanism. All the chambers have pre-amplifiers attached to them, the main amplifiers being in the pile control-room. Initially, as the pile power is raised from zero, the resistor in series with a chamber is changed, so that the chamber measures all powers up to 1 kW without any change of position. (The resistor can be changed by operating a wafer switch outside the pile.) Above 1 kW the chamber is wound out of the pile successively to two pre-set positions, in which the neutron fluxes are a tenth and a hundredth of the flux at the original position. In this way, with only three positions for each chamber, six decades of pile power can be measured. There are eight ionization chamber holes in the pile. The two additional holes are used for experimental work; one of them is used permanently for work with the Gleep oscillator.

Rough temperature measurements are made at four points in the pile by means of resistance thermometers. Two of these thermometers are strapped on to uranium cartridges near the centre of the pile, one is embedded in a uranium dioxide cartridge, and the remaining one is embedded in a graphite cylinder which has been lowered down one of the vertical experimental holes. The temperatures are recorded continuously in the control-room, and it is arranged that if the temperature of the uranium metal cartridges exceeds 60° C. the pile is automatically shut down.

Gleep has only seven experimental holes, so details of all of them are given below:

(*a*) Hole J_1, running from face A to face C through the centre of the pile, 3 in. diameter. Since this hole is along the axis of the pile, and therefore parallel to the uranium holes, it is used for pile oscillator work.

(*b*) Hole J, running from face B to face D through the centre of the pile and thermal column, 3 in. diameter.

(*c*) Hole K, to one side of the thermal column, running from face B to face D, 5 in. × 4 in. The maximum slow-neutron flux in this hole at 100 kW is 3.0×10^{10} n/cm²/sec., and this hole was used for the manufacture of radio-isotopes when Gleep first began operating.

(*d*) Hole L_1, to one side of the thermal column, running from face B to face D, 8 in. × 8 in. This hole can be used for testing the effect on the reproduction constant of the pile of inserting large quantities of material.

(*e*) Hole W, running from top to bottom of the pile through the centre, 3 in. diameter.

(*f*) Holes X and Y, running from top to bottom either side of hole W, 4½ in. diameter.

Although in the foregoing list holes J_1, J and W are all stated to pass through the centre of the pile, they are in fact offset from each other by half a lattice pitch.

Soon after Gleep started operating, the pile control rods were calibrated so that the amount of k they took up when in a given position in the pile was known. This was done by first of all balancing the pile with the control rods so that it was running steadily at low power, then withdrawing the control rods a measured amount, at the same time observing the rate of rise of pile power. From a knowledge of the number of delayed neutron emitters, the half-lives of these emitters, and the rate of rise of pile power, it is possible to calculate the change which has been made in the effective reproduction constant.

Also shortly after the pile started operating, a run was made at 100 kW without the air-cooling system on. As the temperature of the pile rose, the control rods had to be withdrawn in order to keep the power at 100 kW. From the calibration of the control rods and the measured temperature rise, the temperature coefficient of the pile was deduced.

The temperature coefficient depends on the temperature distribution in the pile, but for a pile running without any cooling the temperature is, of course, highest at the centre and falls off towards the edges in much the same way as the thermal neutron flux does. For such a temperature distribution, and for the same change in the graphite temperature as in the uranium temperature at the centre of the pile, the temperature coefficient was found to be:

Change in effective reproduction constant is: -2.9×10^{-5}/°C.

It should be noted that the pile has a negative temperature coefficient, and that this prevents the pile from rising to a very high temperature if, for example,

the control system were to fail. In fact, since the excess k of Gleep is only 2×10^{-3}, a temperature of coefficient of 2.9×10^{-5}/°C. means that the Gleep could only rise 70°C. in temperature before all the excess k disappeared.

The pressure coefficient of the pile was measured in the following way. The pile was run steadily at low power for about half an hour, and then the control rods were set in position. Next, with all the holes in the pile shield closed as well as possible, the extractor fan was switched on. This put the pile under 3.5 cm. of water suction (the mean value as recorded by a manometer on either side of the pile), and the rise in pile power was observed for fifteen minutes.

From the rate of rise of pile power the pressure coefficient was calculated, and the answer obtained was:

Change in effective reproduction constant is: -6.5×10^{-6}/mb.

This coefficient is also negative, since an increase in atmospheric pressure increases the amount of nitrogen in the pile and reduces its reactivity.

In order to check that no dangerous amount of activity was escaping from the stack at high-power running, a 20-atmosphere argon chamber was installed in the top of the stack to measure the gamma activity of the effluent from the pile. During the initial runs at high power, it was noticed that not only did this chamber give a higher current than would be expected from the argon 41 activity, but also that this activity built up with time when working at a constant power level. This suggested that fission product activity was escaping from the uranium in the pile and the following experiments confirmed this.

An aluminium tube was placed through the J hole of the pile. Arrangements were made to flow air through this tube and then over a Geiger-Müller counter. With the pile running at constant power, a given flow of air was passed through the system and the background counting rate caused by the argon 41 was determined. A small foil of bare uranium of known area was then put into the centre of the tube and the counting rate due to the fission products carried away from the foil obtained. This bare foil was then replaced, firstly by samples of the aluminium-sprayed uranium rod, and secondly by a uranium dioxide cartridge. The results of this comparison of bare uranium with the two types of cartridge used in the pile showed that, whereas the aluminium spraying was 99.5 per cent efficient, the uranium dioxide cartridges were leaking gaseous fission products into the air-stream.

In view of these results the channels of the pile containing the uranium dioxide cartridges were blocked from the air-stream. Since they form the outside ring of the pile where the neutron flux (and therefore the heat output) is low compared with the central channels, this did not in fact make the oxide cartridges rise appreciably in temperature when running at 100 kW. The discharge of fission products with the associated build-up of activity on the stack monitor was reduced to a tenth.

Much of the experimental work with Gleep has been done with the aid of an equipment called the Gleep oscillator. This oscillator takes small samples rapidly from the edge of the pile to the centre of hole J_1. These samples are moved in and out of the pile with periodic motion, and this induces a periodic modulation

in the power level of the pile. This periodic modulation in the power level is measured by a boron-trifluoride ionization chamber, is amplified and the resulting signal integrated. The integrated signal is a measure of the change in k produced by a sample.

The samples are housed in a graphite container and can be driven from the outside of the pile shield to the centre of the pile by means of an electromechanical system. The samples are moved between these two positions in a regular manner so as to produce a periodic modulation of the pile power (the samples remain in each position for 30 seconds and take 3 seconds to move from one position to the other).

Electrical apparatus is used in the measurements. The main control unit governs the motion of a sample in the pile. The current from the boron-trifluoride ionization chamber consists of two parts. The first is a steady current, which produces a voltage across the resistor in series with the chamber. This voltage is balanced by a "backing-off" voltage, which is a measure of the mean chamber current. The second component is a periodically varying current due to the periodic modulation of the pile by a sample. The voltage that this produces across the resistor is amplified by the D.C. amplifier.

The voltage output from the amplifier is multiplied separately by sine and cosine factors of the same periodicity as the motion of the sample (this is done by having sliders moving with simple harmonic motion across resistor cards connected to the output of the amplifier), and is then fed into two velodyne integrators and integrated for one complete period.

The integrated answers are thus proportional to the two fundamental components in the Fourier analysis of the pile modulation. If we consider only the first harmonic components in the pile modulation, it may be shown that the percentage modulation (the actual depth of modulation divided by the mean power level) produced by a sample is proportional to the change in k which it would produce if placed at the centre of the pile. Thus the integrated answers are a measure of change in k.

Bepo

The fundamental design of Bepo was undertaken by the U.K. Staff working at the Montreal Laboratory in Canada during 1945-1946. The Department of Atomic Energy at Risley, who were responsible for the engineering design and construction, began work on the project early in 1946. The Ministry of Works, under the direction of the Department of Atomic Energy, began construction in June, 1946, and the work was sufficiently far advanced in two years for the plant to be handed over to the Harwell Research Establishment for final tests and operation.

Bepo is a graphite-moderated, air-cooled pile with a central thermal neutron flux of 10^{12} neutron/cm^2/sec., a critical loading of 28 tons of uranium metal, and a full uranium load of 40 tons giving rise to an excess reactivity which can be used for producing isotopes or for experimental purposes. The air-cooling system was designed to limit the maximum surface temperature of the fuel

elements to 200° C. Loading to critical size took place on 5th July, 1948, the uranium being added channel by channel until the reaction became divergent. The power of the pile was continuously monitored in the sub-critical state by specially-made measuring instruments and when the pile diverged the power was permitted to rise to 50 watts, with no coolant flowing, before the reaction was shut down by the automatic safety system. In the ensuing months the pile was gradually worked up to full power, the design maximum flux being reached by Christmas, 1948.

As Harwell was established in a vacated aerodrome which included four large hangars, it was possible for the construction of the pile to proceed at once under cover by using one of them as the pile building, although a section of the roof had to be raised 20 feet to provide additional head-room above the pile for handling tall experimental equipment. The cooling air exhausters required a new building and this was constructed adjacent to the selected hangar, to which it is connected by underground air and service ducts.

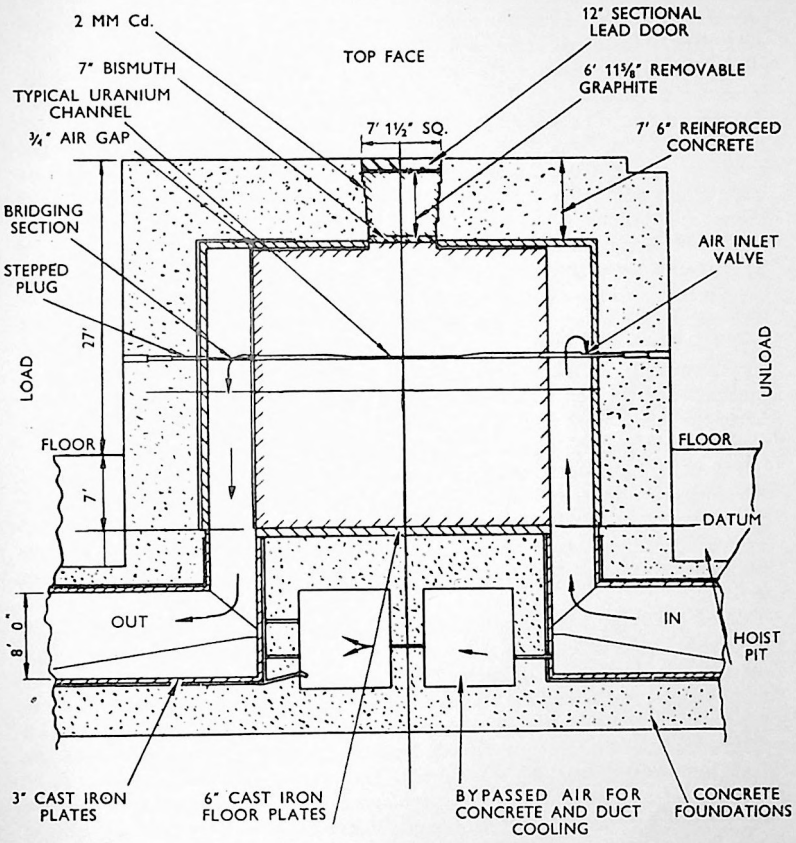
A considerable volume of air is required to cool the pile (about 180,000 cu. ft./min.) and this is drawn through the pile, in a single pass system, by a number of exhausters situated between the pile and the main exhaust stack. Filters are installed in the air intake to clean the air before it is passed through the pile and another set between the pile and the compressors to remove any trace of radioactive dust that might arise in the pile itself before the air reaches the main machinery, which discharges into the base of a stack 200 ft. high.

Since materials introduced into the pile are radioactive on removal there is within the pile building a concrete storage block with accommodation for some five tons of irradiated uranium cartridges (usually called "slugs") and numerous other cells where irradiated materials can be stored temporarily on removal from the pile until they have decayed sufficiently for safe handling. Irradiated material from the pile has to be withdrawn direct from the pile into lead flasks and a feature of the pile building is the overhead crane system to permit of the easy handling of these heavy flasks.

The general construction of the pile itself is shown in the diagram (Fig. 9). The reacting part is a cube of graphite of 26-foot side through which pass 1,849 channels about $3\frac{1}{2}$ sq. in. in cross-section and pitched at $7\frac{1}{4}$ in. centres. The central 900 of these channels can accommodate bars of uranium machined into cylindrical rods, 12 in. long by 0.9 in. diameter and encased in aluminium to prevent oxidation of the uranium and the escape of fission products into the cooling air-stream.

Twenty uranium bars are included in each channel, leaving three feet of empty channel at each end. The channels are loaded radially outwards from the centre to form a right cylinder of 10 ft. radius, 20 ft. long. The remainder of the graphite around this central core serves to reflect neutrons which would otherwise escape from the central system.

In addition to the main channels this graphite moderator is perforated with holes for experimental purposes so that the actual structure is somewhat complicated. It is built up of standard blocks each $7\frac{1}{4}$ in. $\times$ $7\frac{1}{4}$ in. $\times$ 29 in. long with



ELEVATION

Fig. 9. Sketch showing longitudinal section of Bepo.

features machined in their surfaces which provide when assembled all the necessary holes. 850 tons of graphite required machining into some 25,000 blocks with more than 60 variations in the basic types, and this work was executed in a workshop specially erected for the purpose at Harwell. The general machining tolerance adopted was $\pm$ 0.0025 in. on all dimensions and such accuracy was maintained that, on completion, the total height of the 26 ft. stack was correct to within 0.03 in. From the top and one side cubes of graphite called "thermal columns" project from the main moderator. These columns by virtue of their distance in graphite from the nearest source of fast neutrons provide a source of almost pure thermal neutrons.

The 900 central channels are connected at both the air inlet and air outlet ends by headers 4 feet wide and extending over the whole graphite face. The headers are connected to the 10 ft. $\times$ 8 ft. underground ducts of the main air system. The main outer structure of the pile consists of a reinforced concrete and steel shell lined with 6 in. thick cast-iron plates, and constitutes the biological shield for attenuating the intense radioactivity within the pile. The radiation level outside when the pile is running at full power is only twice that which exists when the pile is fully shut down, thus ensuring that the sensitive instruments used for experimental work are not adversely affected by background activity.

The 6 in. cast-iron shield provides an initial large attenuation of thermal neutrons and gamma rays so that the bulk of the radiation energy escaping from the reflector is converted into heat in a conducting and heat-resistant material from which it can be easily transferred to the cooling air-stream circulating past the sides of the cast iron. In this way high temperatures in the concrete are avoided.

When the graphite moderator was stacked stringent precautions were taken to ensure clean conditions so as to exclude dust and other impurities with high-capture cross-section for neutrons, which might prevent the pile reacting. To obtain these conditions (not usually available on a construction site) the shield was built as a complete box, the air ducts and all holes through the shield sealed off, the inside of the pile scrupulously cleaned and lightly pressurized with clean air before graphite stacking was started. The entire shield therefore had to be constructed as a unit and one of the problems in the construction of the pile was the extreme accuracy with which the pile shield comprising some 3,000 tons of concrete and 600 tons of steel had to be assembled in order that continuity and alignment of the 3,800 holes common to both graphite and shield were preserved.

The method adopted was first to level and set the cast-iron baseplates, on which the graphite is stacked, to within $\pm$ 0.01 in., then to erect on this base the steel-frame structure of walls and roof. On this structure the 6 in. cast-iron shield plates and the tubes through the shield were set to $\pm$ 0.01 per cent in 3 ft. "lifts", each lift being concreted in turn, great care being exercised to ensure that the concrete penetrated to all interstices in the shield and that no voids or cracks were left to provide subsequent leakage paths for radiation.

The pile is loaded by pushing in a row of slugs from the charge face of the pile, and unloaded by means of steel push-rods which push the irradiated

uranium slugs out through the unload face into a lead-shielded container. A bridging section is provided connecting each uranium air channel with a hole through the shields so that the uranium bar can cross the air headers. The holes through the shield are of course plugged to prevent the escape of radiation at all times other than when an individual channel is being loaded or unloaded. It can be seen from the diagram (Fig. 9) that all holes through the shield are stepped so that no direct path is provided for escape of radiation. Loading and unloading machines are carried on 12-ton hydraulic hoists extending the width of the pile and can be positioned accurately to any horizontal row of shield holes on the load and unload faces of the pile and traversed on the hoists to select the requisite hole in a given horizontal row.

As explained earlier, the pile is cooled under induced air draught, which was preferred to forced draught in order to establish a negative pressure within the pile with respect to atmosphere and so ensure that any leakage of air at the many holes through the shield wall would involve fresh air inwards and not activated air or dust outwards. Although this results in less advantageous conditions at the exhausters than a forced draught system, it is fully justified in practice by the greater simplicity of the experimental arrangements.

The basis for the specification of the cooling system was the air quantity and pressure drop required through a central uranium channel in order to keep the temperature of the hottest uranium cartridge below 200° C. for a rate of heat release corresponding to a total power of four megawatts. The heat release per unit length along a channel and from channel to channel across the pile is not uniform since the distribution of neutrons in a pile is a maximum in the centre and falls off towards boundaries. In order to economize in pumping power the air flow down each channel is adjusted to suit its heat release.

Five 1,400 h.p. single-stage compressors running as exhausters are installed to draw the air through the pile, of which four are required for the full power conditions. The drive for each exhauster is from a direct-coupled 11,000-volt, three-phase induction motor supplied from the National Grid through suitable step-down transformer and control gear.

The pile is controlled by introducing four boron-carbide-filled hollow steel rods 2 in. in diameter horizontally into the side of the pile so that, when fully inserted, the rods extend across the reacting core. These rods can be accurately positioned from push-buttons in the control-room. In addition there is a second system of 10 similar rods, known as shut-down rods, operating vertically in the pile and having two positions only, right in or right out.

When both systems are fully inserted the fission rate within the pile is about a milliwatt since the boron in the rods absorbs thermal neutrons very strongly. The start-up procedure is first to withdraw the shut-off rods, then the control rods to a position where it is known that the pile power will rise at a reasonable rate; when the desired power is reached the rods are moved in until the indicated power level is steady. In subsequent operation compensation for self-induced changes in the reactivity of the pile must be made by control-rod movement. These changes occur owing to variation in the graphite and uranium temperatures

and the build-up of certain fission products with a high neutron-capture cross-section. All the self-induced reactivity changes tend to shut the pile down so that subsequent to start-up a continued outward withdrawal of the control rods is necessary for several days until steady conditions are reached. This adjustment was originally effected by hand but an automatic regulating system has now been installed which not only relieves the operator of a tedious task but also maintains a more steady power level than can be achieved by hand control, a desirable feature for experimental work.

The shut-down rods, controlled by compressed air, are available at all times to shut down the pile rapidly in under a second if faults should arise in the plant.

The power of the pile is measured in two ways. The first is by means of a heat balance measurement in the cooling air. This, although accurate, has a slow response owing to the inherent thermal time-lags of the system, and therefore is of no use for the instantaneous control of the pile. The second is by measuring the thermal neutron flux. This method, which is sensibly instantaneous, employs ionization chambers within the pile shield which produce a small electric current proportional to the thermal neutron flux in which they are immersed. This output is amplified and displayed on suitable instruments in the control-room.

In the control-room there are instruments indicating activity gained by cooling air on passing through the pile, while γ and thermal neutron health monitors, permanently installed around the pile, are connected up in a similar way.

APPENDIX C

SCIENTIFIC PAPERS BY A.E.R.E. STAFF

The following is a list of the papers by members of the Atomic Energy Research Establishment which have been published in the scientific and technical press in the period from the foundation of the Establishment to the end of June, 1951. In some instances authors have moved to other places since their papers were published. A supplementary list of papers published between 1952 and 1954 is obtainable from H.M.S.O., reference A.E.R.E. Int./Bib. 96.

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APPENDIX D

READING LIST AND GLOSSARY

To aid those who are not familiar with all the technical terms used in this account, a glossary has been prepared defining the more important of them. Some readers may wish for something wider than definitions, so for them a list of elementary and general books on atomic energy and nuclear physics is given before the glossary. To this list are added some more advanced works for students of science who are not specialists in nuclear and atomic physics, and a short list of books and papers on the use of nuclear fission to produce power.

READING LIST

ELEMENTARY AND GENERAL WORKS

(Books suitable for the non-scientist)

ANDRADE, E. N. DA C. The atom and its energy. London, G. Bell and Sons Ltd., 1947.

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(Published papers on this subject by members of Harwell staff are listed in Appendix C. See particularly papers by Sir John Cockcroft)

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Nucleonics 4, No. 2, pp. 2-16 (February, 1949).

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Rev. of Economics and Statistics, *31*, No. 3, pp. 217-228 (August, 1949).

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Bull. of Atomic Scientists, *4*, pp. 115-21 (1948).

OLIPHANT, M. L. The industrial application of atomic energy.
The Engineer, CLXXXIX, No. 4911, pp. 303-4 (10th March, 1950), and No. 4912, p. 323 (17th March, 1950).

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Discovery, *9*, pp. 78-82 (1948).

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GLOSSARY

ALPHA PARTICLE
A positively charged particle emitted by radioactive substances such as uranium and radium. It is identical with the helium nucleus.

ATOMIC STRUCTURE
The atom consists of a central nucleus of positive electric charge, around which, and at relatively great distances away, *electrons* revolve in orbits. The nucleus is made up of *protons*, each of unit positive charge, and *neutrons*, which are uncharged. Electrons each have unit negative charge and in the neutral atom their number balances the number of protons in the nucleus.

The number of protons in the nucleus is known as the *atomic number* of the element, and this determines its chemical properties. Because all nuclei of the same atomic number have the same chemical properties, irrespective of the number of neutrons within the nucleus, and occupy the same place in the periodic system, they are known as *isotopes*. The sum of protons plus neutrons within the nucleus gives the *mass number* of the isotope.

BETA PARTICLE
High-speed electron emitted during disintegration of radioactive elements.

BETATRON
A machine for accelerating electrons to high speeds in a circular path by the electric field produced by a changing magnetic flux. (See pp. 50, 51.)

BREEDER PILE
A nuclear reactor which produces more fissionable atoms than it consumes.

CARRIER-FREE ISOTOPE
A preparation of a radioactive isotope which is practically free from stable isotopes of the same element.

CHAIN REACTION (nuclear)
After a uranium 235 nucleus captures a neutron, fission occurs and neutrons are released; these in turn cause fission in other uranium 235 atoms, which release yet more neutrons to cause further fissions. This is a chain reaction.

CLOUD CHAMBER
An instrument, consisting of a glass chamber containing air super-saturated with water vapour, in traversing which charged particles leave visible tracks of water droplets.

CONTROL ROD
A neutron-absorbing rod used to control the power level at which a nuclear reactor (q.v.) works.

COSMIC RADIATION
Very penetrating radiation reaching the earth from outer space.

CURIE
The unit of radioactivity. It is so defined that one gram of radium has an activity of one curie. For general purposes this is the quantity of a radioactive isotope which disintegrates at the rate of 3.7×10^{10} disintegrations a second.

CYCLOTRON
A machine which accelerates protons and deuterons to very high speeds in a spiral path. The particles are kept in a spiral by a large magnet, and the accelerating voltage is produced by a radiofrequency transmitter.

DEUTERIUM
The isotope of hydrogen of mass 2; often called heavy hydrogen.

DEUTERON
The nucleus of the deuterium (q.v.) atom.

ELECTROMETER
A sensitive instrument for measuring small electrical charges.

ELECTRON
See *Atomic structure.*

ELECTRON VOLT (eV)
A measure of the energy of a particle. One electron volt is equal to the kinetic energy which a particle carrying a charge equal to that of the electron would acquire in falling through a potential drop of one volt.

FISSION
The splitting of an atom into two or more approximately equal fragments (the *fission products*). Fission is accompanied by the emission of neutrons and much energy.

GAMMA RADIATION (gamma rays)
Electromagnetic radiation similar to X-rays, but of shorter wavelength. It is often emitted by radioactive substances in discrete amounts called quanta.

GEIGER COUNTER (or Geiger-Müller counter)
An apparatus for counting charged particles by means of the ionization they produce in a gas.

HALF-LIFE
The period of time taken for the activity of a radioactive substance to decay to half its original value, i.e. for half the atoms originally present to decay. This may vary from a fraction of a second to millions of years, according to the element and isotope.

HEAVY WATER
Water in which a considerable fraction of the molecules contains deuterium (q.v.) instead of hydrogen.

ION
A positively (or negatively) charged atom or molecule, i.e. one which has lost (or gained) one or more electrons. A neutral molecule in solution may thus form two ions, one positive and one negative.

IONIC EXCHANGE
A process in which ions from two different molecules exchange partners. Thus AY and BZ can become AZ and BY.

IONIZATION CHAMBER
A chamber in which the passage of charged particles is detected by means of the ionization which they produce.

ISOTOPE
See *Atomic structure.*

"k"
See *Reproduction constant.*

LINEAR ACCELERATOR
A machine in which electrons are accelerated to high speeds in passing down a straight evacuated tube (or waveguide). The acceleration is caused by electromagnetic waves in the tube.

MAGNETRON
A kind of wireless valve for the generation of very high frequency oscillations, up to 10,000,000,000 per second.

MASS NUMBER
See *Atomic structure.*

MASS SPECTROMETER
An instrument for separating atoms according to their weight. Used in isotope separation and analysis.

MESON
A short-lived radioactive particle intermediate in mass between an electron and a proton.

MODERATOR
Material used in a nuclear reactor to slow down fast neutrons without capturing them.

NEUTRON
An elementary particle of size and mass approximately that of the proton, but without electrical charge. See also *Atomic structure.*

NUCLEAR REACTOR
A structure in which a chain reaction in fissile material can be maintained and controlled.

NUCLEUS
See *Atomic structure.*

PHOTODISINTEGRATION
The disintegration of a nucleus, with the ejection of one or more constituent particles, by γ-rays.

PHOTOFISSION
Nuclear fission induced by γ-rays.

PILE
"Pile" is sometimes used as a synonym of nuclear reactor (q.v.), but more usually only as a name for a reactor using natural uranium as a fuel and graphite as a moderator.

PILE PERIOD
A measure of the time taken in a nuclear reactor for the neutron population to increase or decrease when the equilibrium is disturbed.

PROTON
The nucleus of the hydrogen atom and a fundamental particle in the structure of nuclei of other elements. It carries unit positive charge and has unit mass. See also *Atomic structure*.

QUANTUM
See *Gamma radiation*.

RADIOACTIVITY: RADIOACTIVE DECAY
The property possessed by certain atoms of exploding spontaneously with the emission of a charged particle (α, β or proton) and, usually, gamma radiation.

RADIOGRAPHY
Technique of examining solid objects by photographing the shadows which x- or γ-rays cast on passing through them.

RADIOTHERAPY
Treatment of disease with ionizing radiation.

REPRODUCTION CONSTANT
Measure of the reactivity, or the rate of multiplication of neutrons, in a nuclear reactor.

ROENTGEN
The roentgen is the unit of radiological dose and is defined in terms of the amount of electric charge released by the ionization caused by x- or γ-rays. One roentgen corresponds to the release of 83.8 ergs of energy in a gram of air, so that it would take the energy of 100,000 roentgens to warm the gram of air by 1° C.

SAFETY ROD
A control rod which in an emergency can very quickly shut down a nuclear reactor.

SCINTILLATION COUNTER
Instrument for detecting particles by the flashes of light they cause in certain crystals.

SPECIFIC ACTIVITY
Radioactivity of unit mass of the radioactive substance.

SYNCHROTON
A machine for accelerating electrons to high speeds, similar to the betatron (q.v.) but using synchronous electric impulses, and not a changing magnetic field, to accelerate the electrons. Proton synchrotrons are being developed.

THERMOCOUPLE
A device for measuring temperature in terms of a voltage produced at the junction of two dissimilar metals when heated.

'RACER
Small quantity of radioactive isotope used to follow biological, chemical or other processes.

TRITIUM
The isotope of hydrogen, of mass 3.

TRITON
The nucleus of tritium.

WAVEGUIDE
A metal tube with its dimensions so chosen that the electromagnetic waves can be transmitted along it.

VAN DE GRAAFF ELECTROSTATIC GENERATOR
This machine provides a potential of several million volts by the accumulation of electric charge conveyed to an insulated conductor by a continuously moving belt. This potential can be used for the acceleration of charged particles.

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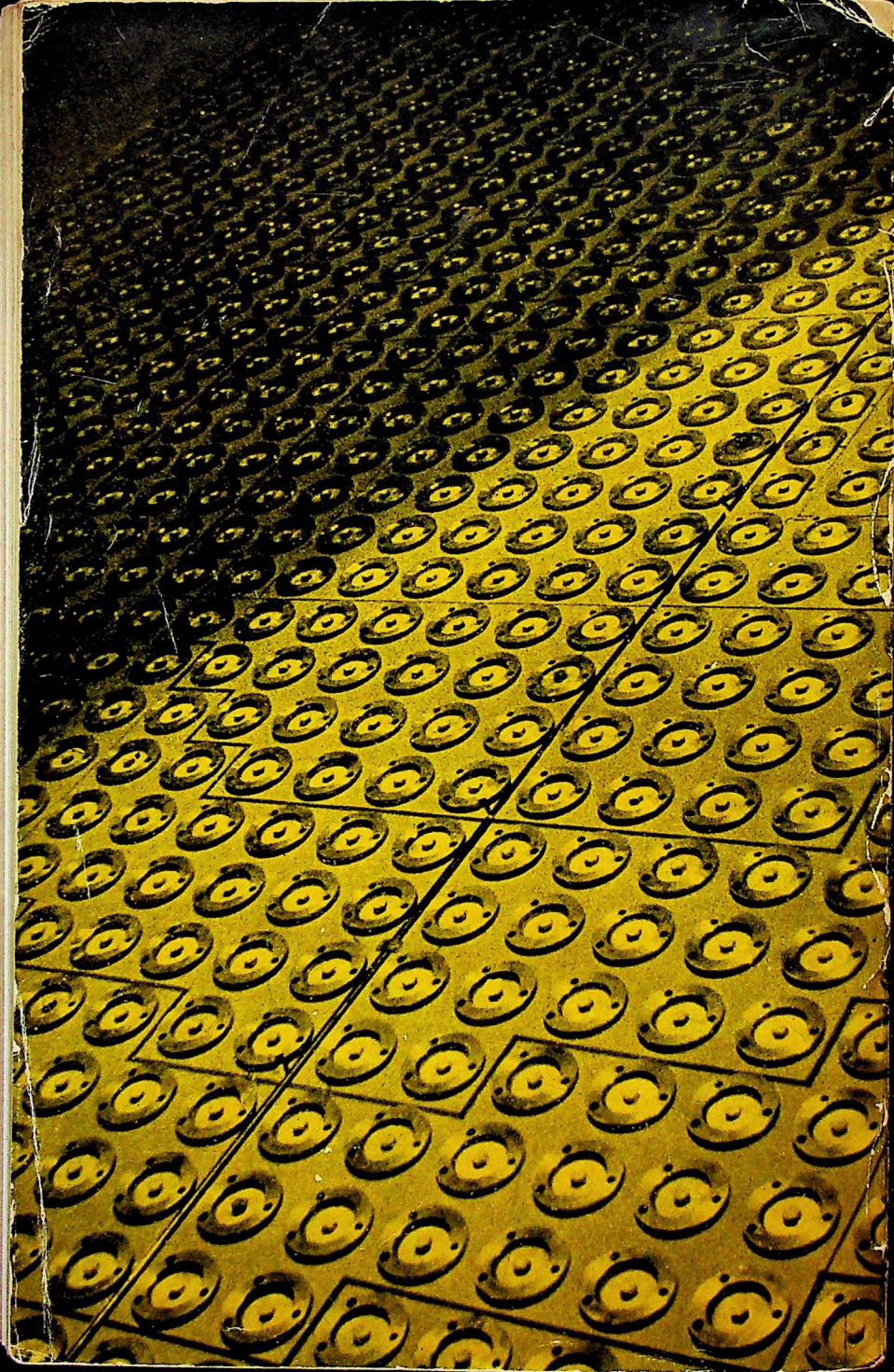
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